

CELLVIVAL OUTCOMES:
THE EFFECTS OF AN EDUCATIONAL VIDEO GAME
ON STUDENTS' UNDERSTANDING AND MOTIVATION

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CELLVIVAL OUTCOMES: THE EFFECTS OF AN EDUCATIONAL VIDEO GAME ON STUDENTS' UNDERSTANDING AND MOTIVATION

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There is a sizable and consistent literature theorizing how to design games to be educationally effective but there is currently conflicting empirical evidence on the benefits of educational games, even games designed based on these theories. To address this, a video game was specifically developed based on these theories to teach high school students evolutionary biology. 98 Students from 10 classes across 5 schools in New York State were assessed in terms of content knowledge, motivation, and depth of understanding before and after participating in the game module and typical instruction. The research design was a combination of switching replication and a Solomon 4-group design. It was found that when the game was used after typical instruction on the topic, some groups saw limited gains in multiple choice scores, short answer depth, and motivation measures. There was a strong order effect where students that received typical instruction on the topic first and then participated in the game module saw the greatest benefits. However students that received the module first may have seen gotten less out of typical instruction. This suggests that game-based lesson can be beneficial or detrimental and must be used carefully to be effective. These findings have many limitations regarding sampling and fidelity.

BIOGRAPHICAL SKETCH

Andrew Jefferson lives in Freeville with his wife Jessica.

Dedicated to all students who are underserved

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INTRODUCTION

There is a strong literature and a lot of theories about how to design educationally effective games but there is much less work empirically testing those designs and testing what kinds of benefits they have in the classroom.

Theories of Educational Video Game Design

Reviewing these theories of design, there is a lot of work that has been done (Burnes et al., 2015; Annetta, 2010; Amory, 2007; Habgood, 2007; Fisch, 2005; Bizzocchi & Paras, 2005; Bruckman, 1999; Dempsey, Lucassen, Hayes, Casey, 1996). Looking across disciplines there are common themes that emerge and common suggestions for how to build educationally effective games. One of the main principles is that the content of interest should be integrated into the mechanics of the games. A designer should build what they want students to get out of the experience into the rules of how the game works. Beyond that, this literature suggests general principles of good game design: that a game should be appropriately challenging and it should provide meaningful choices.

To explore why the literature converges on these principles, let us consider what they mean and how they are based on established theories. This will demonstrate why they provide strong arguments for what we would expect to be effective, though there is little direct empirical support.

Integrated educational content

The phrase “well integrated educational content” can be most clearly illustrated with a contrasting example. Let us imagine a game where you are navigating a maze and you frequently come to a locked door where you have to answer a math problem about angles in order to continue navigating the maze. This is an example of content

that is not well integrated with the mechanics of the game. The ‘educational content’ of the math problems is completely separate from the core experience of navigating the maze. It is often referred to as ‘divorced content’. The educational content is actually literally an obstacle to participating in that experience, which is likely what attracted the player to the game. It has even been argued that this kind of design can actually implicitly communicate to the player that the educational content is not ‘fun’ and is something you have to work through to be rewarded with the fun part of the game (Papert, 1998).

In contrast, imagine you want to teach the exact same content about math problems involving angles so you create an artillery game. A game where the player must solve these kinds of problems in order to hit the target they are aiming for. In this case, these problems are well integrated into the core experience of the game. It would be difficult separate them or to replace the math problems with other content. In the maze game, the math problems could be easily replaced with, for example, geography questions because of the separation but in the artillery game it would be much harder. Additionally, the artillery game can demonstrate how this skill can be applied to solve problems. Rather than being an arbitrary obstacle to something the player enjoys, the educational content is something useful that helps them achieve their goals. The game’s design demonstrates how it can be valuable.

This is the main principle the literature converges on. The game should be “placing educational *content* at the heart of game play, so that children engage in the targeted real-world behavior or thinking as they play the game” (Fisch, 2005, pg 1). That content should not be divorced from the rules of the game but deeply integrated into them. Designing a game to do this is more difficult than adding content onto divorced mechanics, but it means that if players are engaging with that game they are also engaging with the content at some level because they are so closely linked.

General game design and motivation

This leads us to the other principles which focus on good game design, educational or otherwise (Salen & Zimmerman, 2004). This makes sense: if you design a game such that if players engage with the game they are also engaging with the educational content, you then need to make sure the game engages players. These principles include that the game should provide an appropriate level of challenge and that it should provide meaningful choices. These are good guidelines for all games but here we will review how these principles have a strong basis in established motivational literature.

Self Determination Theory

One of the major theories of motivation is Self Determination Theory (SDT), which addresses how the perceived source of rewards and punishments affects one's motivation to perform a task (Ryan & Deci, 2000a; Ryan & Deci, 2000b; Deci et al., 1991; Benware & Deci 1984). It distinguishes between extrinsic and intrinsic motivations. Extrinsic motivations come from a source outside the individual, such as getting paid to do something. Intrinsic motivations come from within the individual, such as finding something enjoyable or interesting in itself.

To further explore this distinction, consider a student in a classroom from the perspective of SDT. Grades and penalties can be seen as extrinsic motivators; they are imposed on the student by the teacher. These kinds of motivators can communicate to the student that they are performing a task in order to please someone else, not because they find it enjoyable themselves. This can make students less likely to perform those tasks on their own. Colloquially, this kind of phenomenon is often described as “I used to like doing it, but then I got paid to do it so now it feels like work and I don't like doing it anymore”. SDT addresses how extrinsic motivators can damage one's intrinsic motivation to perform a task.

On the other hand, it also addresses how one can create intrinsic motivation by associating a task with something the individual already finds intrinsically motivating. Returning to the classroom, this can take the form of individualizing a lesson. Say a teacher wants to teach a student math and knows this particular student is interested in space; the teacher may show the student how math can solve rocketry problems. In effect, the teacher shows how this new skill or knowledge is relevant to goals and interests the student already has, so the new content is seen as useful and interesting.

If one wants to create intrinsic motivation in a more general audience, this requires finding things that are interesting to a general audience. This requires appealing to very broad interests such as desires to feel competent or like one is in control of their own life; that they have a sense of autonomy.

Player Experience of Need Satisfaction (PENS)

This leads to more recent motivational work on PENS theory, which looked at applying SDT specifically to video games (Rigby & Ryan, 2011). This work looked both at describing how video games create the high levels intrinsic motivation that have repeatedly been found (Toprac, 2011; Rosas, Nussbaum, & Cumsille, 2003; Russell, 1994; Randel & Morris, 1992; Malone, 1981) and how to translate this into concrete design recommendations about how to foster intrinsic motivation. Player enjoyment and tendency to persist in playing a particular game was best predicted by how well the game supported the player's experience of satisfying the needs for competence, autonomy, and relatedness (which is outside the scope of the current work). In other words, games that support a sense of competence and autonomy in players are better at creating intrinsic motivation. So what mechanics support a sense of competence or a sense of autonomy?

Providing an appropriate level of challenge supports a sense of competence in the player. This builds on ideas like Vygotsky's zone of proximal development (Berk

& Winsler, 1995) and Csikszentmihalyi's concept of flow (Csikszentmihalyi, 1990). If a task is too difficult it will frustrate a player and if it is too easy it will bore them; a task that requires some effort but it is possible for them to succeed at will create a sense of accomplishment, a sense of competence.

This has implications not just for the difficulty of game but for designing feedback systems as well. These systems can highlight when players have achieved a goal, fostering that sense of achievement and competence, but can provide even more value when players fail. Then the feedback can provide scaffolding to help players do better next time and eventually succeed, creating an even greater sense of competence by being able to learn from failure and improve. For example, the rhythm game Dance Dance Revolution provides feedback after every button press about how precise it was, scaffolding better timing in the future and telling players when they are perfectly timed.

A sense of autonomy can be supported by providing meaningful choices, so the player feels a sense of control over the events of the game. "Meaningful choices" here means informed choices that have consequences. So the player is making choices that will have a lasting impact on the state of the game and they have enough information about what those impacts will be to weigh their options.

These kinds of choices can occur at various levels of gameplay. In the original Super Mario Bros., when to jump can be seen as a meaningful choice; the player has a sense of the arc and what will happen if they jump from various places, and if they fail to jump various hazards they will die. They have information the choices and their choices have consequences. At a more strategic level, in more recent games like Mass Effect from Bioware, there are a variety of characters asking for the player's aid, some of them mutually exclusive. Deciding which characters to help affects the story and resources available later in the game, and again the player has some idea what those

differences will be when they make those choices. Two players may end Mass Effect with very different experiences because of these choices and feel like they had some control over that experience.

Implications for educational video game design

In light of this motivational work, these common principles seem well grounded and supported. Beyond integrating the content, one should make games that create a strong intrinsic motivation to continue playing. This can be done by providing an appropriate level of challenge to support a sense of competence and providing meaningful choices to provide a sense of autonomy. Previous work provides strong arguments that we would expect such games to be educationally effective, though there is little direct empirical evidence to support this.

Previous Educational Video Game Findings

Why is there little evidence to support this? Reviews of work on educational games have repeatedly found that the evidence for educational video games' effectiveness is 'inconclusive' (Honey & Hilton, 2011; Hays, 2005). These reviews also offered insight into the limitations of this work

Limitations of previous games research

The primary limitation is simply that there is not much work on this topic. What work does exist is fragmented between disciplines that use different terminologies and methodologies, making it hard to compare.

The more recent National Research Council report also includes a more detailed list of common issues (Honey & Hilton, 2011). Researchers in this area often fail to define specific learning goals that a game is trying to address, fail to describe how the game is intended to meet those learning goals, and then fail to use measures that address the learning goals that they had previously failed to define. Further, many

researchers fail to provide appropriate control groups and look at the game as part of a larger curriculum. This means that it is hard to separate the effects of the game from the effects of other activities during the curriculum.

Limitations of previous games

Beyond the research problems, this work is also problematic because many educational games are not designed based on the principles previously described. Previous work done during the ‘edutainment boom’ looked at games that have since been widely criticized (Dondlinger, 2007; Bruckman, 1999; Papert, 1998). Many of the theories and frameworks behind those principles were direct responses to the flaws of games during this period. Common issues included a focus on extrinsic rewards (such as points), offering the player few choices, little sense of agency, and no interactivity beyond answering questions. Some were described as taking a “flashcard approach” to describe the lack of engaging content (Kirriemuir & McFarlane, 2004; Parker & Lepper, 1992; Lepper, 1985). On top of this misuse of game-based motivational systems such games also tended to have low production values and lack high-quality interface, graphics, sound, or narrative (Dempsey, Lucassen, Hayes & Casey, 1996). All these factors likely contributed to the finding that most of these games would not be voluntarily played outside of schools (Leddo, 1996) and were repeatedly found to be ineffective educationally (Kerawalla & Crook, 2005; Trushell, Burrell, & Maitland, 2001).

These types of games are known to be ineffective but are still being produced (McLeod, 2009). This creates another obstacle to trying to evaluate the effectiveness of games based on the previous principles; ineffective games not based on those principles will also be categorized as ‘educational games’ and likely be included in such reviews. This provides another layer of noise to evaluating games based on the previously described principles.

Previous well-designed games

Recently there has been work on games that are well-designed based on these principles. Projects such as Quest Atlantis (Barab, Gresalfi, & Ingram-Goble, 2010), Outbreak @ the Institute (Rosenbaum, Klopfer, & Perry, 2007), and Mad City Mystery (Squire & Jan, 2007) are working to try and apply these principles to develop tools. However even these have limitations, especially for looking at how to effectively use games in typical classrooms. Mad City Mystery and Outbreak @ the Institute both use augmented reality, where participants use smartphones or other devices and movements in the real world affect the game world. These approaches are great for engaging the players and drawing connections between the game actions and the real world but such location based play is hard to generalize to other locations and difficult for most teachers to pickup and use.

The example of *Supercharged!*

In this regard, the work on a game called *Supercharged* provides a very informative example of how to effectively use games in the typical classroom (Squire, Barnett, Grant, & Higginbotham, 2004). For context, the game attempted to integrate the principles of electrostatics in physics, or how magnetic fields work, into the game play. The way this works is the player is trying to navigate their spaceship through a maze but they have limited fuel for direct thrust. What they have is the ability to change the ship's charge, changing if it is attracted to or repelled by various charged objects in the environment. In fact the game's levels have two phases; a setup phase where a limited number of charged objects can be placed to aid with navigation and a play phase of actually controlling the ship.

The intent of the project was to help students develop an intuitive sense of how these fields interact and how attraction and repulsion work. These fields have been historically hard to visualize or grasp. To measure its success, the game was tested in

three urban middle school science classrooms. It was found that students who received the game had higher performance on pre-post measures compared to students who received typical instruction, such as a better grasp on the role of distance. It is one thing to read that the strength of the field decays exponentially; it is another to experience how much more your ship is attracted to an object as you get closer to it and then to draw on those experiences to navigate a maze successfully. Both groups were equally able to describe fields but the game students referenced in-game challenges, whereas typical instruction students' responses tended to appear more recitations of memorized material.

In evaluating *Supercharged!*, the researchers not only found it was educationally effective but provided important insights into implementing video game-based lessons in current classrooms. Initially teachers did not know to use the video game and just let the students play it. This led to students quickly becoming bored when they had 'beaten' the game and not understanding how the experiences in the game related to the rest of the class. The teachers and researchers then developed handouts for students to record their experiences, scaffolding reflection on what they were doing and why. The teachers also lead discussions of how different students had approached the game's challenges, what they had learned, and how it related to the physics of electrostatics. The students then got much more out of the game with this scaffolding and these explicit connections. It highlighted the importance of not just providing teachers with a game but with the tools and guidance on how to use the game effectively in a classroom; most teachers are still not familiar with using educational video games and their support can be instrumental in helping students effectively transfer ideas from the game to the real world.

The design and evaluation of *Supercharged!* provides an examples of good educational game design and the important insights that can be gained by studying

such games in real world classrooms. Such work can address not only the possible benefits of such games but how to best use them in classrooms.

The Current Investigation

The goal of this project was to test the effects of a video game that deeply integrated educational material into the mechanics of the game in a classroom setting. The research questions are how does the game module affect 1) content knowledge, 2) deep understanding and the ability to reason about problems, and 3) motivational outcomes related to the material compared to typical instruction on a given topic? The topic of interest is evolutionary biology with a particular focus on how and why a population can change over time in response to selective pressures.

To answer these questions, a video game that deeply integrated these ideas was developed and tested in classrooms at schools across New York State.

MATERIALS AND METHODS

In order to answer these questions, a game, a module using the game, and an assessment were developed.

Materials

Game

As discussed, there are few available games that satisfy these principles of good educational game design. To address this, a new game called *Cellvival!* was developed to allow empirical testing of the effectiveness of these design principles. It was developed in partnership with the ASSET (Assisting Secondary Science Education with *Tetrahymena*) program and designed to tie into the ASSET program's other lab modules. Toward these ends, the game focused on helping teach evolution; as a basic topic in biology it could then easily be connected to other labs. At the same time, evolution presented a complex dynamic system that a video game might be able to represent and allow experimentation with more effectively than other methods. After generating the initial design, it was refined through meetings with Walker White, the head of Cornell's Game Design program.

Once the initial design was ready, a team of artists and programmers were recruited and production of the game itself began. Much of the core engine and interface work were contributed by Aleksey Polesskiy and later refined by Scott Warren, Timothy O'Brien, Fernando Ito Tadao, and Ryan Pindulic. Polesskiy also contributed to the design of the population system in the game. For art, Lauren Cruvellier and Jessica Roth contributed animations and other assets. Additionally, local high school students were involved in the production process and also contributed art and music assets.

The final game allows students to explore the impact of reproductive choices over multiple generations and how these choices influence an organism's fitness within the context of a specific environment. Students play as a single *Tetrahymena* cell attempting to survive while gathering enough resources to reproduce. When they reproduce, they make choices that affect the next generation of *Tetrahymena* cells. They then play as another cell that is a member of that subsequent generation, again attempting to survive and gather enough resources to reproduce. The iterative nature of the game allows students to experience how their choices affect the survival rate of subsequent generations, to observe how small changes accumulate across generations, and to explore what traits are favored in specific environments.

In this way, the game design seeks to communicate the educational content through gameplay in a way that is consistent with the previously discussed principles of effective design. Rather than presenting textual content about selective pressures, students experience challenges that favor different sets of traits. Similarly, by playing through multiple generations, they see how changes accumulate as a core part of the game rather than as an abstract concept. There are continuous meaningful choices at different levels, from the moment-to-moment navigation while avoiding predator to the reproductive decisions, which are scaffolded with informational feedback and affect future gameplay. Pilot testing in local schools also helped tune the predators and amount of food to provide students with appropriate challenges. All these various aspects of the game were designed to convey the content in an integrated, engaging way.

More detailed descriptions of the game itself and the production process are included in Appendix A and Appendix B, respectively.

Game module

One major issue with deploying games to the classroom is that most teachers are not familiar with video games or how to use them effectively in the classroom (Simpson, 2005). To address this issue, teacher and student handouts to accompany the game were developed with the assistance of ASSET program staff, including former high school science teachers. Specifically the teacher handout described how to use the game as part of a two-period module that could easily be fit into an existing curriculum. It included a full lesson plan for both days of the module that cycled between sessions of gameplay and in class discussions about those experiences and how they related to biology. The self-contained nature of the module, detailed guides to the game and possible discussions, and premade student handout attempted to make the game as easy as possible for teachers to become familiar with the game and confidently use it in the classroom.

A full copy of the teacher handout is included as Appendix C and the student handout is Appendix D.

Assessment

To address the research questions, the assessment included three types of items. As in previous work assessing student's knowledge of evolution, a combination of multiple choice and open-ended, short answer items were used (Ha, Haury, & Nehm, 2012; Sinatra et. al., 2003). Multiple choice items allow assessing understanding of key concepts without using much class time but have noted limitations (Stanger-Hall, 2012) that can be addressed by also including open-ended items. These types of items also have been used to examine evolutionary reasoning as well as knowledge in previous work (Nehm & Ha, 2011) making them well suited to these question of interest. The items used were based on publicly available exams of

evolutionary principles and refined again with the assistance of ASSET program staff, including former high school science teachers.

To examine motivation, a series of Likert scales were developed. Such scales have a long history in motivational research and have recently been the instrument of choice for looking at situational interest in classrooms (Sun & Rueda, 2012; Rotgans & Schmidt, 2011; Guthrie et al. 2004). The items specifically asked about topics and activities specific to the module as well as broader areas like general interest in science. This was done to assess changes in motivation and interest related to the module and to test if they generalized to other areas.

An example of the assessment can be found in full in Appendix E.

A follow-up questionnaire collected demographic information about students and teachers' ratings of each student's motivation and performance in class.

Methods

Research design

The research questions are about change, so the basic research design is a pre-post study looking at the change in responses on the assessments based on treatment. However there are a number of other concerns to be addressed.

One concern was gathering adequate, useful comparison data. Recruiting teachers and students to spend class time on assessments without allowing them to use the intervention would have been difficult. Additionally, if there were game and non-game groups, students from the non-game group may have been frustrated to be “left out” and their game-group peers may have talked about the game and even showed them the game, complicating results. To address this concern, a variant of a switching replications design was used. It allows each group to provide information on both

treatments and on any order effects. On the practical side, it also means all students participating get to experience the game at some point. This was more appealing to the teachers and minimized possible issues from students.

Another concern was the possibility of pretest sensitization or practice effects. Since the same assessment was being given three times, there was a concern student performance would simply improve through repetition even in the absence of treatment effects. A design that addresses this issue is the Solomon -4 group design, where some group receive pretests and other do not. This allows one to both measure pre-post changes and to measure the impact of the pretest itself on those changes.

The final design combined a Solomon 4-group design and switching replications design to produce 4 groups (Figure 1). This is actually a simple 2 x 2 design, where the conditions are Pretest vs No Pretest (or 2 assessments vs 3) and Game First vs. Game Second.

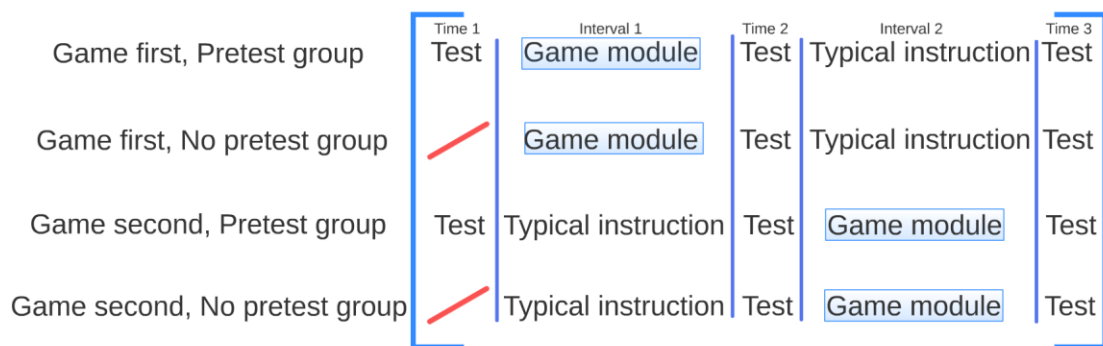


Figure 1: The four groups of the research design and the timeline for each group.

So students in the Game First, Pretest group take the assessment, then spend two class periods doing the game module, then take the assessment again, then they spend two days doing their teacher's typical lessons on evolution, then they do the assessment a final time.

Students in the Game First, No Pretest group do not do the initial assessment before the game module, but then follow the same sequence as the Game First, No Pretest group.

Students in the Game Second, Pretest group do the pretest but then do typical instruction first and do the game module after the second assessment.

Students in the Game Second, No Pretest group do not do the pretest, and do the typical instruction and then the game module.

Classes were randomly assigned to conditions.

The assessments were administered online through Qualtrics' website.

The only difference in the assessments was that at Time 3, there were additional short answer questions at the end, asking students about the overall experience.

Participants

Teachers were recruited through a high school biology teacher online forum. Five teachers from different schools across New York State volunteered to participate in the study during the fall term of 2014 (from September to December). They had a total of 169 students across 10 classes. A breakdown of the age and sex of students by class and teacher is found in Table 1. The students in class 5 were in 8th grade living Environment, while the rest of the classes had a mix of 11th and 12th grade students. They were predominantly white (83%).

Table 1

Breakdown of Students by Teacher, Class, and Sex

Teacher	1*		2*		3	4				5	
Class	1	2	3	4	5	6	7	8	9	10	Total
Male	14	9	3	2	14	6	10	3	11	5	77
Female	14	16	8	3	13	12	2	7	-	11	86
Blank	-	1	-	-	1	-	3	-	-	1	6
Class Totals	28	26	11	5	28	18	15	10	11	17	169

Note that teachers indicated with asterixes (*) taught only AP biology classes.

RESULTS

The data collected show that the game module provides some limited benefits under certain conditions. In evaluating these benefits, the results show that the order of presentation is a significant factor in the effects of the module. There were significant participation issues that limited the analysis.

Compliance

Surveys were collected from 169 students. There appear to have been fidelity issues at both the student and teacher levels. The patterns of assessment completion are described in Table 2: For each class for each teacher the table lists the condition for the class, the appropriate Times for assessments to be completed, and the number of students in the class who completed those assessments (the bold rows). Below that, it shows the other patterns of assessment completion also seen in that class and how many students displayed that pattern (i.e. completed the assessments at those times).

In all classes there were a few students who failed to complete one or two assessments, perhaps having missed the day the assessment was given. The cumulative effect reduced the amount of available data. Greater problems are seen in classes 1, 7, and 9 (highlighted) where the majority of students failed to complete the proper assessments; this may indicate a more systematic problem such as an issue at the instructor level. The students may have been given too many or too few assessments by the instructor, leading to greater compliance issues and further reducing the amount of usable data.

Table 2 <i>Breakdown of Students by When they Completed Assessments, Class, Teacher, and Group</i>		
Class Number & Group	Assessments Completed	Number of Students
Teacher 1*		
1: Pretest, Game First	1, 2, 3	1
	1	8
	2	2
	1,2	18
2: Pretest, Game Second	1, 2, 3	18
	-	1
	1	1
	1, 2	2
	3	1
	2, 3	3
Teacher 2*		
3: No Pretest, Game Second	2, 3	9
	2	2
4: No Pretest, Game Second	2, 3	4
	2	1
Teacher 3		
5: No Pretest, Game Second	2, 3	23
	2	3
	3	2
Teacher 4		
6: Pretest, Game First	1, 2, 3	14
	1	1
	2	1
	1, 2	1
	1, 3	1
7: No Pretest, Game First	2, 3	1
	1	1
	2	2
	1, 3	1
	1, 2, 3	10
8: Pretest, Game Second	1, 2, 3	8
	1	1
	2, 3	1
9: No Pretest, Game Second	2, 3	0
	1	3
	3	2
	1, 3	6
Teacher 5		
10: No Pretest, Game First	2, 3	12
	-	1
	2	2
	3	2

In total, 90 students had full data for the assigned condition (and only the assessments for that condition) and these students were used for the subsequent analyses. Of these students, each condition was unevenly split between AP and non-AP students (Table 3). Some conditions had too few students when looking at only AP students or only non-AP students, so all the compliant responses were pooled across class levels.

Table 3 <i>Breakdown of Students by Class Level and Group</i>			
Group	Number of compliant AP students	Number of compliant Non-AP students	Total compliant students
Pretest, Game First	1	14	15
No Pretest, Game First	12	1	13
Pretest, Game Second	18	8	26
No Pretest, Game Second	13	23	36

Statistical Analyses

All analyses were done with the R statistical package (R Core Team, 2015). Except where noted otherwise, linear mixed models used and through the ‘lme4’ package (Bates, Maechler, Bolker, & Walker, 2014) to produce the reported t-statistics and p-values.

The set of analyses used was based on previous work on how to analyze

Solomon-4 group designs (Braver & Braver, 1988). First responses were analyzed to test for an interaction of the fixed effects of game order and pretest presence, with Class nested within Teacher included as hierarchical random effects. This was done to ensure there were no pretest sensitization effects interacting with the treatment effect of the game module. Then the effects of the module were tested either pooling pretest conditions or separately within the Pretest and No Pretest groups as described in the previous work. This procedure was repeated across timepoints (for total scores) or intervals (for gain scores).

Multiple Choice Responses

The multiple choice questions were designed to measure students' knowledge of important evolutionary concepts. It was expected that students in typical classes and the game module would show improvement but those in the game module might show greater improvement. The data show that those who get the game do have greater improvement but only if they get the game after typical instruction; the order of presentation is an important factor.

Tests of the two pretest groups at Time 1 found no significant differences in terms of initial multiple choices scores.

Total scores

Total multiple choice (MC) scores were calculated for all the students at each Time. No pretest sensitization effects interacting with the treatment effect of the game module were found, either at Time 2 or at Time 3.

Then main effects were examined. At Time 2 there were no significant effects. At Time 3 there was a significant effect of the game module ($t(3)=4.368, p<.05$) and a marginal effect of the number of tests ($t(2.5)=3.483, p<.1$). (Note: the main effects tests were effectively a 2x2 test rather than an ANOVA, resulting low degrees of

freedom). Figure 2 shows the MC scores for all four groups of students at Time 3. For both Pretest and No Pretest groups, the Game Second groups show greater scores at Time 3 compared to the Game First group

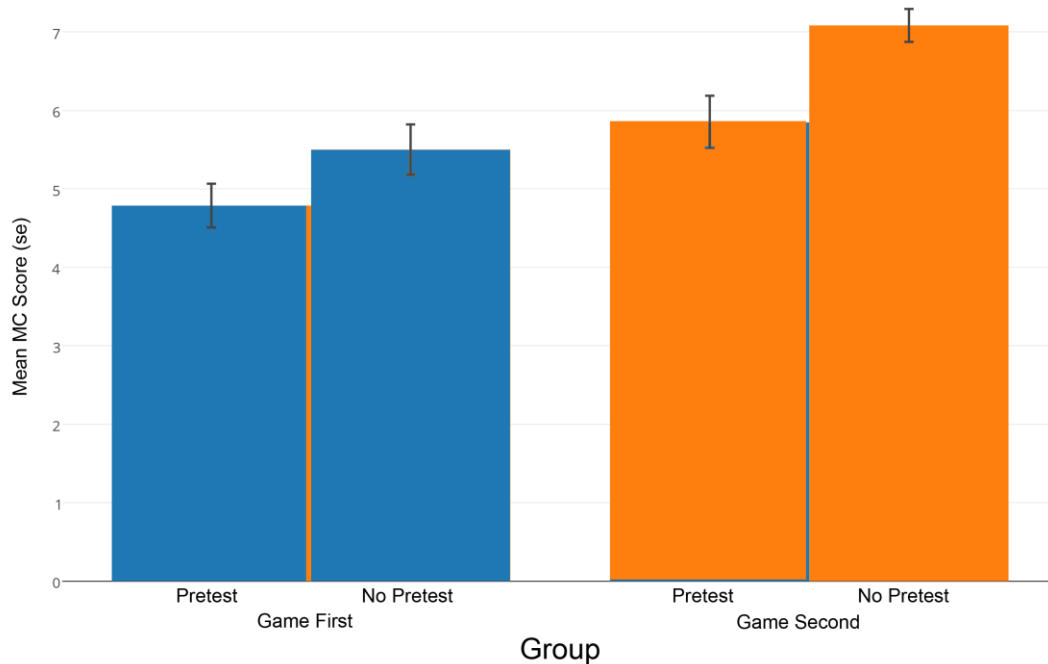


Figure 2: Mean MC score at Time 3 for all groups by pretest and presentation order

This suggests that the game module produced better outcomes on the MC items compared to typical instruction but only when the game module was presented second. It appears that after receiving typical instruction, receiving the game module lead to greater gains in MC scores than receiving typical instruction after the game module.

Gain scores

To directly evaluate if receiving the game module lead to greater gains in MC scores than receiving typical instruction, the MC scores were also used to compute gain scores for each student and these were also analyzed. Between Times 1 and 2 the only factor that significantly affected the gain scores was the initial score at Time 1

($t(27)=-4.254, p<.001$). That is to say the presence of the game did not significantly affect the gain score and the higher the initial score the lower the gain score, indicating there may have been a regression to the mean effect.

Between Times 2 and 3 there were significant effects of the game order ($t(92)=4.318, p<.001$), the initial score at Time 2 ($t(92)=-8.654, p<.001$), and the number of tests ($t(92)=3.310, p<.01$) on the gain scores. These differences between groups can be seen in Figure 3. The groups that received the game module second (the orange bars on the right) had greater positive change scores between Times 2 and 3 compared to the groups that received the game module first (the blue bars on the left). However, the non-prettested groups appear to have higher positive change on top of this (the 2nd and 4th bars from the left) compared to the prettested groups (the 1st and 3rd bars from the left), so there may also have been some kind of ‘test fatigue’ effect.

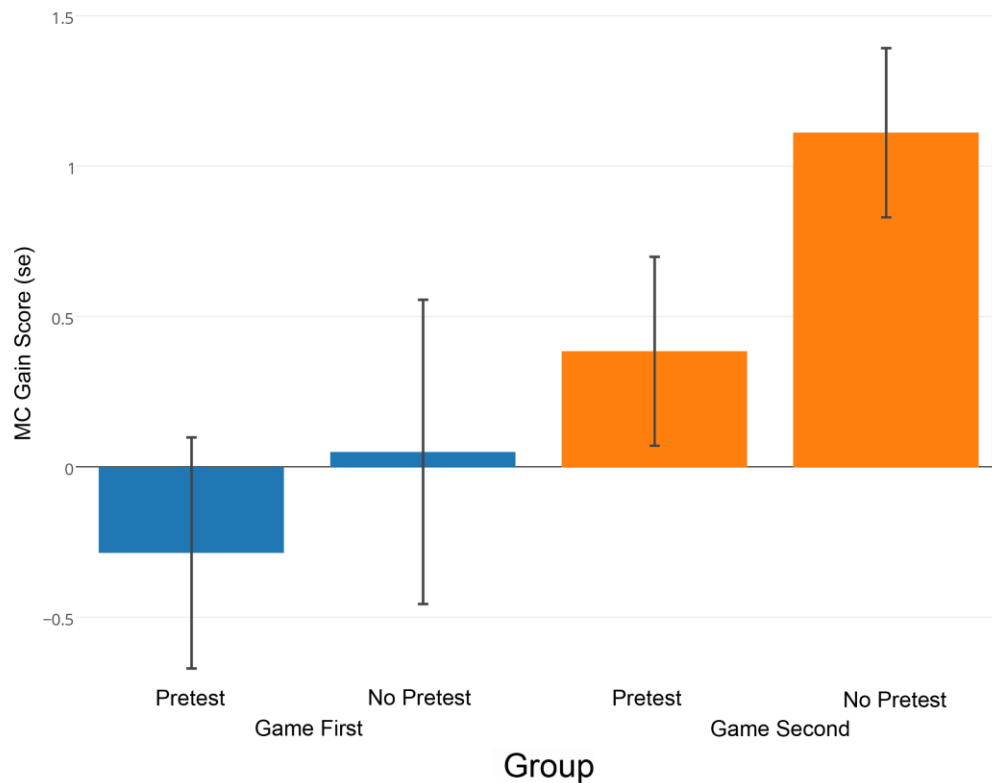


Figure 3: Average MC gain scores from Time 2 to 3 across all groups.

To further examine the apparent importance of order of presentation, the gain scores for the pretest groups were tested across interval, game order, and initial MC score (for that interval) and a significant 3-way interaction was found ($t(72)=2.024$, $p<.05$). This interaction is visualized in Figure 4, split between looking at the gain scores during Interval 1 (from Time 1 to 2, on the left) and during Interval 2 (from Time 2 to 3, on the right). In both sections, all the lines trend to the lower right, indicating that students with higher initial MC scores for that interval tended to have lower gain scores compared to students who initially scored lower.

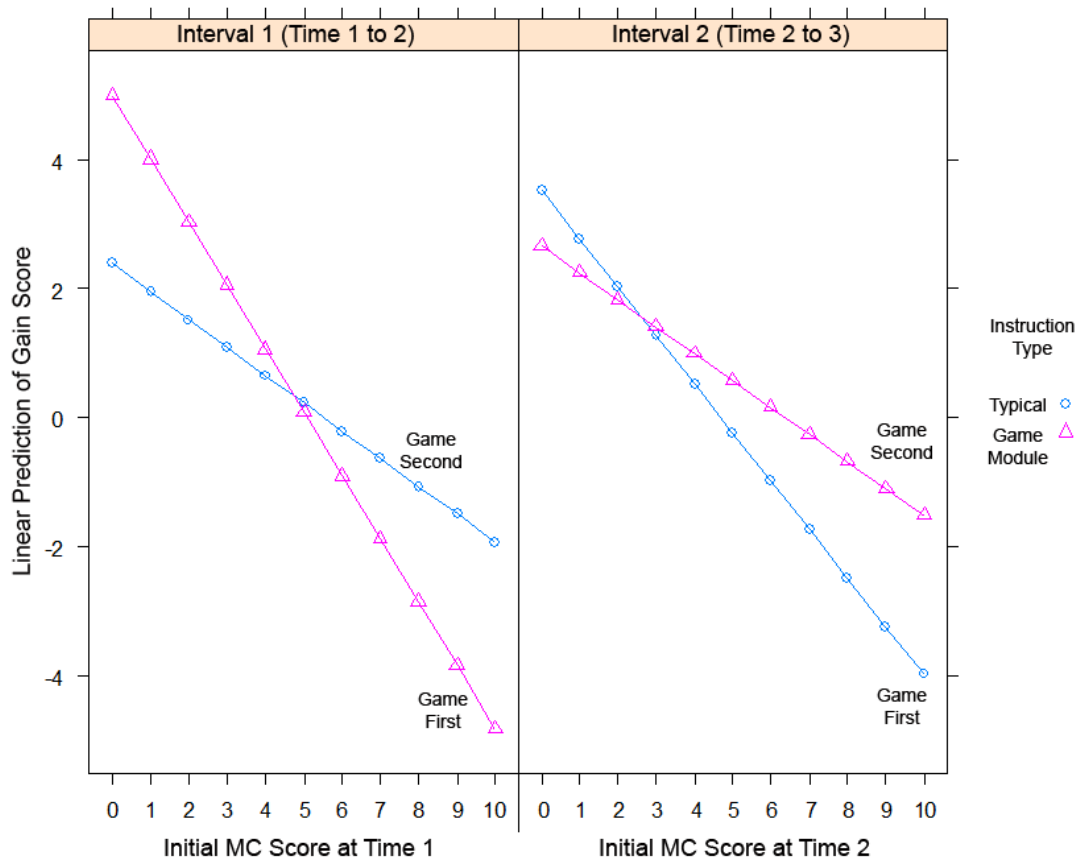


Figure 4: MC gain scores by interval, instruction type, and initial MC score.

The interaction effect can be seen in the subtle difference between the lines for the Game First group (as indicated). The Game Second group shows a very similar pattern across both intervals; those with the lowest initial MC scores for the interval gained a little over 2 points and the highest initial scores gained about -2. It appears they remained consistent across the typical instruction and the game module. The Game First group shows a more exaggerated version of this pattern during Interval 1; the lowest initial scores had higher gains of a little over 4 points and the highest initial scores had lower gains of under -4 points. This suggests the game module, with no introduction through typical instruction, may have been more effective for low initial scoring students but less effective for high initial scoring ones. Then during Interval 2, when this group then received typical instruction, the pattern shifts slightly; while student who initially scored high are still gaining about -4 points, the gains for those with lower initial scores have decreased. The low initial score students are now seeing gains more similar to the Game Second group, while the high initial score students see much lower gains.

It appears the Game First group during Interval 1 presents an interesting trade-off compared to the typical instruction in the Game Second group, benefiting lower scoring students at the cost of the higher scoring ones. In Interval 2 these benefits are then mitigated when they receive typical instruction, leaving the Game First group overall with lower gain scores compared to those of the Game Second group that is now getting the game module.

Revisiting AP student effects

It is also worth noting that while AP and non-AP students may have important differences that make pooling them problematic, the order effect does not appear driven by AP status. In Figures 2 and 3, the No Pretest, Game Second had the highest

total MC scores and gain scores, while the No Pretest, Game First Group was lower in both cases. Yet Table 3 shows the No Pretest, Game First group was almost entirely AP students while the No Pretest, Game Second group is predominantly non-AP students by almost 2-to-1. This strongly suggests that these greater gains are not AP students out-performing other students but an effect of the order of presentation.

For thoroughness, these analyses were also run separating the AP and non-AP students to just look at the effects of game order. While there were not enough students in each of the four groups to look at pretest presence and game order, there are enough compliant students if they are pooled by collapsing the pretest groups. For the AP students this leaves 13 in the game first group and 31 game second and for non-AP 15 game first and 31 game second. Looking at the MC scores and gain scores for the groups divided this way, no groups showed significant effects of game order.

Other factors: sex and motivation

Sex of the student did not have any significant effect or interact with the game module, in terms of MC scores or change in scores.

Teachers' ratings of student motivation from the follow-up questionnaire were examined to look for group differences and to test if motivation interacted with the effects of the game module. There were significant differences in student motivation between the groups both by game order and pretest presence ($t(6)=-2.426, p<.05$). As seen in Figure 5 it appears the Game Second, No Pretest group had significantly higher motivation compared to the other groups. This is problematic as a confounding variable and will be discussed as a limitation of the study.

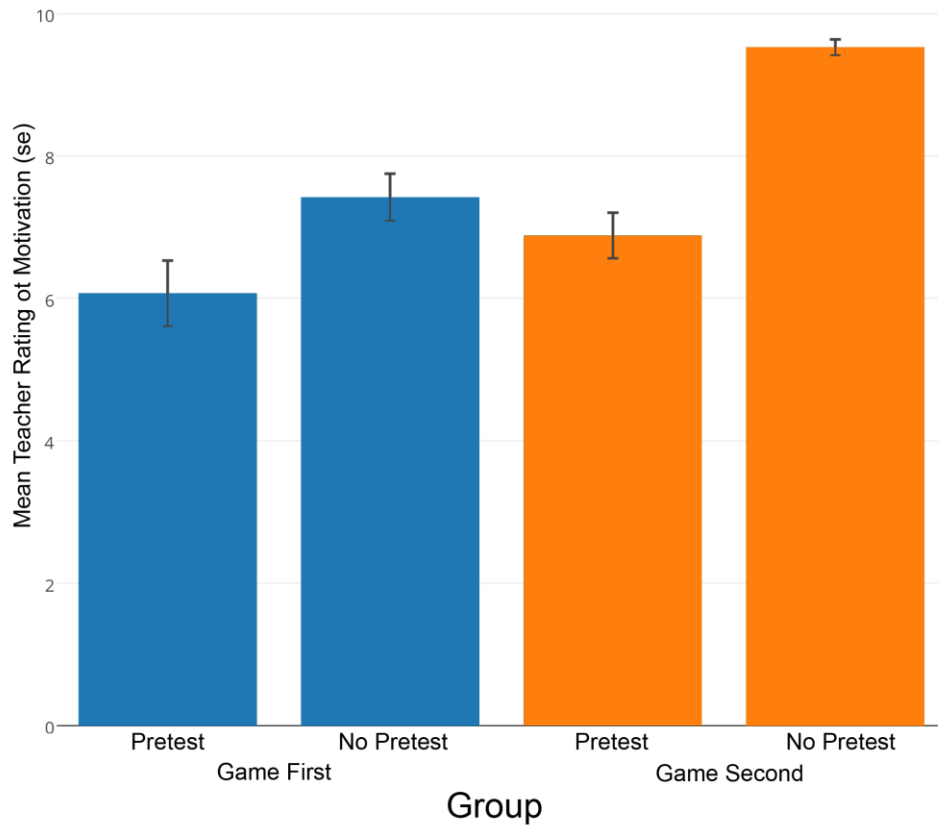


Figure 5: Average teacher ratings of student motivation by group

It is particularly problematic as motivation rating was found to have a significant effect on MC scores. At Time 2 there was a positive main effect ($t(91)=2.438, p<.05$) while at Time 3 it interacted with the order of presentation ($t(91)=3.082, p<.01$) such that the higher a student's motivation the higher their MC score if they were in a Game Second group. This interaction was also found for the MC gain scores at Intervals 1 & 2 ($t(89)=2.396, p<.05$).

This interaction is particularly notable, since games may themselves be motivating and help increase interest in class material. If a game module increases interest and motivation and more motivated students get more out of a game there could be a positive feedback loop. This brings us to the interest scales.

Interest Scales

The interest scales were designed to measure how participating in the game module might affect student interest in related topics and their willingness to participate in related activities. The game module's effects were limited to interest in closely related topics and activities and did not extend to science in general or to activities outside the classroom. Like the MC results, order also played a significant role but even on the few scales that were affected the results were mixed.

Similar analyses to the total score and gain score analyses performed on the MC scores were performed on each of the ten interest scales seen in Figure 6.

Please rate your interest in the following activities:

	No interest	.	.	Some interest	.	.	High interest
Learning about science	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Doing interactive science activities	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Reading about science	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Discussing science in class	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Discussing science outside of class	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Discussing biology in class	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Discussing biology outside of class	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>

Please rate your interest in the following topics:

	No interest	.	.	Some interest	.	.	High interest
Science	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Biology	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Natural selection	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>

Figure 6: Assessed interest scales

Student ratings from 1-7 on these scales were analyzed both for main effects and for differences in gain scores. It should be noted that for almost all the change scores, the initial score had a significant effect indicating there may have been some form of a 'regression to the mean' effect here as well.

Across all ten scales, only one showed any effects between Times 1 and 2. There was a main effect of the game, where students who had the game module between Times 1 and 2 showed a significant negative effect on interest in discussing biology in class ($t(17)=-2.184, p<.05$). So the game only effects closely related interests and, without preparation, affects them negatively.

There were more positive effects on more scales when the game module was between Times 2 and 3. In terms of main effects, the game had a significant positive effect on interest in doing interactive science activities ($t(9)=2.467, p<.05$). In terms of change scores, there were significant 3-way interactions for the scales looking at interest in interactive science activities ($t(86)=-2.753, p<.01$) and the topic of natural selection($t(81)=-2.153, p<.05$). In both cases, the order the game was given and whether students received the pretest interacted with the students' previous interest rating. The effects appear similar as well. When the results are broken down by pretest, as shown in Figures 7 and 8, the only difference appears in the responses from the Pretest, Game Second group (the triangle points on the left in both figures). In both figures, the students in the Game First groups (as indicated, the circle points) who initially rated their interest lower at Time 2 (as marked at the bottom of the figure) increased their ratings by more at Time 3 compared to the students who rated their interest higher Time 2. As mentioned before, this may be partly a regression to the mean effect from the students who rated the interest high at Time 2. It could also be that students who were initially less interested were more impacted by the typical instruction they were receiving during this interval.

The students in the Game Second groups (as indicated, the triangle points of both figures) display different effects. Those who were not pretested (on the right) show a similar pattern of decreasing gains with increasing initial rating but the pattern is much more pronounced than it was for the Game First students. Students at the lower end of the scale tended to have much greater gain than those who initially were more interested. This could indicate that the game is more effective at increasing interest in students who were initially uninterested than the typical instruction. In contrast, looking at interest in the topic of natural selection (Figure 8) for the Pretest, Game Second group (triangle points on the left) actually shows a much less pronounced version of this effect. This could suggest the additional testing either lead to stronger anchoring to previous ratings or that it somehow mitigated the interest gains seen in the No Pretest, Game Second group. Looking at interest in doing interactive science activities (Figure 7) for the Pretest, Game Second group (triangle points on the left) shows the one reversal of this pattern, with students who initially reported lower interest showing lower gains. Something about the interaction of being pretested and receiving the game second resulted in reversal from the Game First pattern or the more pronounced No Pretest, Game Second pattern.

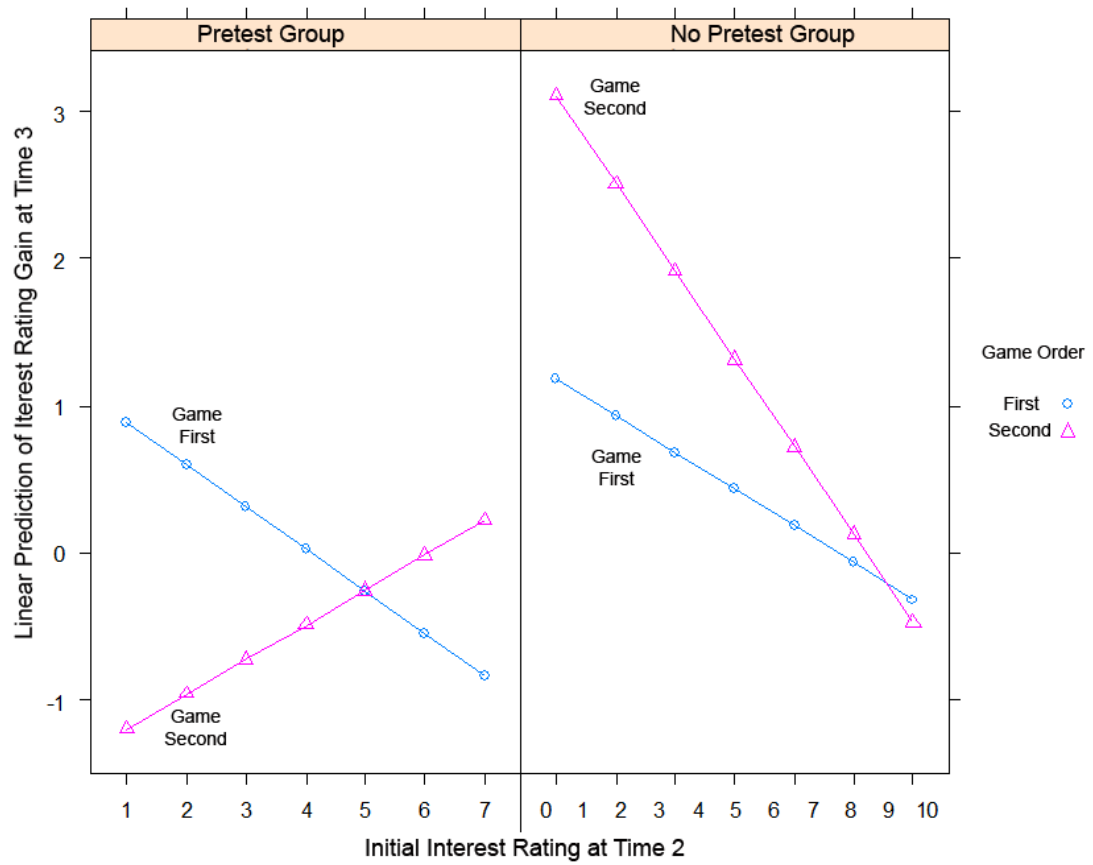


Figure 7: The 3-way interaction in students' interest rating gains at Time 3 for 'doing interactive science activities' between game order, pretest, and initial rating at Time 2

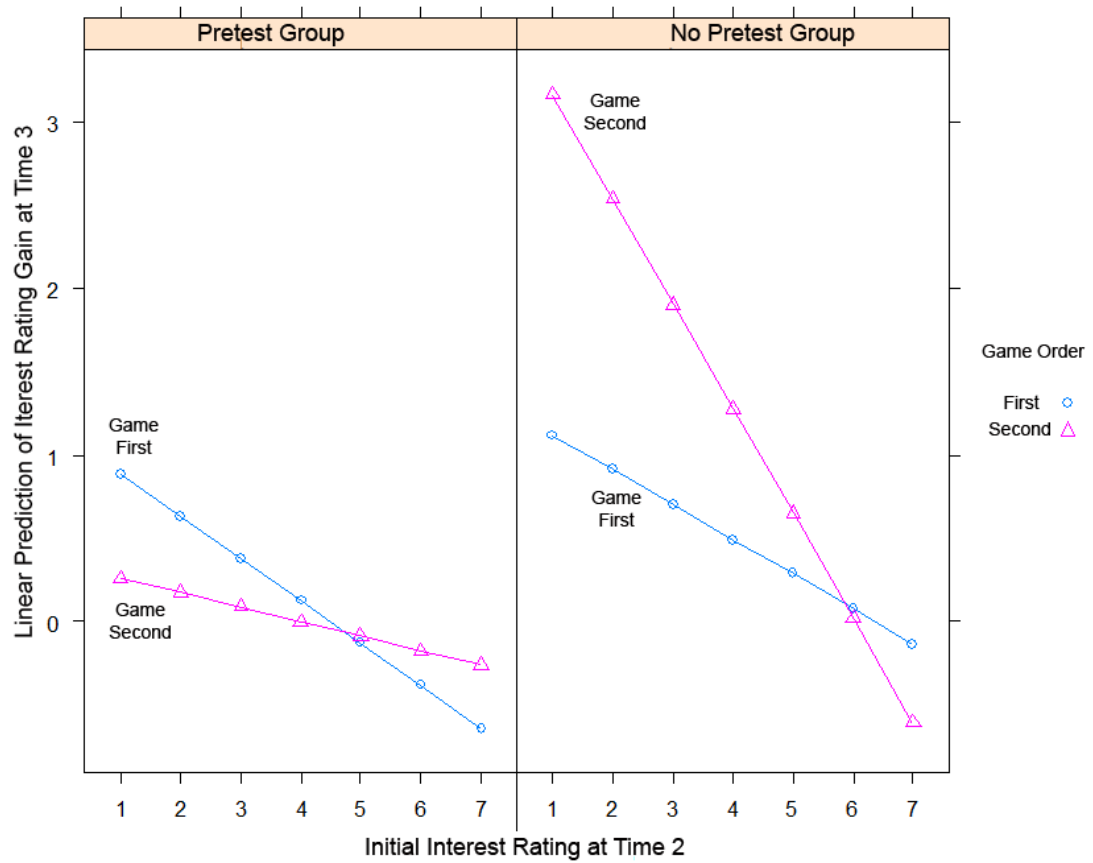


Figure 8: The 3-way interaction in students' interest rating gains at Time 3 for the topic of natural selection between game order, pretest, and initial rating at Time 2

None of the game module's effects on the interest scales remained significant when a sequential Bonferroni adjustment was used to correct for the multiple comparisons across all items and timepoints.

Summarizing across interest scales

Between Times 1 and 2 the only effect appears to be that the game module decreased reported interest in discussing biology in class. Between Times 2 and 3 the game had more complicated effects on interest in both discussing science in class and the topic of natural selection: For No Pretest students, low interest students reported greater gains from the game compared to typical instruction. For Pretest students, high interest students reported greater gains in interest in interactive science activities from game while low interest students reported lower gains, compared to typical instruction. A less severe version of this pattern was seen in the interest in the topic of natural selection.

The game had very limited effects on the interest scales. The only effects were on scales very closely related to the module and even there the results were mixed.

Short Answer Responses

The short answer questions were intended to look at how students thought about problems and how they responded to open-ended prompts. It was expected that students who had received the game would have a deeper understanding of evolutionary processes and mention deeper, structural components of the problem rather than focusing on superficial elements. This appears to be the case for the item about natural selection, but it also lead to poorer responses on definitional item and mixed results when looking more closely at the specific markers within the responses.

For reference the short answer questions were:

“Question 6:

Briefly describe what makes one organism "more fit" than another, in the context of natural selection.

Question 7:

A population of cougars (a type of large cat) have recently moved into the habitat of a population of mountain goats and have begun preying on the goats. Give an example of how this change may impact the population of mountain goats.

Beyond there being less goats, how might the population change?

Question 8:

For organisms that sexually reproduce, how do they select a mate?”

Qualitative coding

In order to compare the short answer responses, each response was coded on a number of dimensions. The responses to each question were reviewed and used to generate a number of common markers or themes whose binary presence or absence could be used to evaluate all responses. These markers were intended to indicate depth of understanding or provide insight into how students approached the question. For example, Question 6, about what makes one organism more fit than another, had markers that included whether the responses mentioned the environment, survival, reproduction, passing on traits, or reproducing more than others, in any form. These types of markers were also combined with an evaluation of coherence and response quality to generate a continuous “depth” rating. The markers and rubric for rating response depth for each question can be found in Appendix F.

Length and depth ratings

The ratings of overall depth for questions 6 and 7 are fairly straightforward. There were no pretest effects, and no main effects (other than initial rating). For Interval 1, the only significant effects on depth were a negative effect on the change scores for Question 6 ($t(33)=-2.359, p<.05$). This may indicate that typical instruction better prepared students for this question, in this case being able to articulate what makes an organism fit. As there were no differences found at Time 3, it appears that either the Game First group recovered or the Game Second group was reduced to the same level; consulting the mean gain scores for depth for each group at those times it appears that the Game Second group was reduced to the level of the Game First group, as shown in Figure 9.

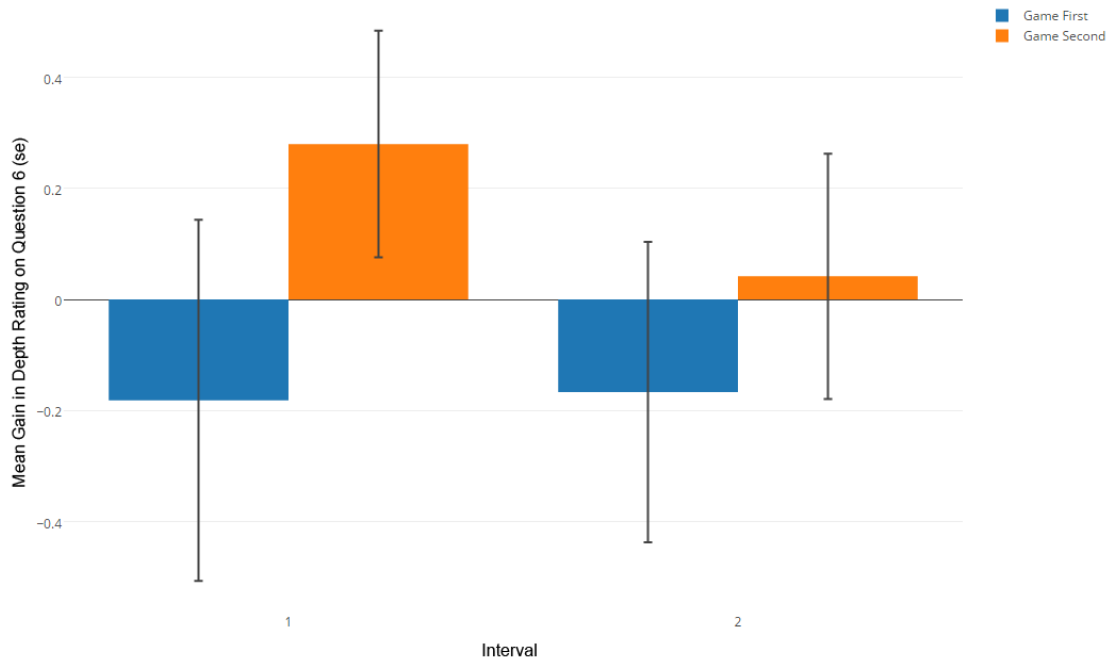


Figure 9: Gain in depth rating on Question 6 by game order and interval

For interval 2, the game module had a significant positive effect on the change in depth ratings for responses to Question 7 ($t(5)=3.031, p<.05$). This suggests that, with the preparation of typical instruction, the game module may better prepare students to write about problems involving selective pressures.

This contrast between the change in depth ratings between Questions 6 and 7 is interesting. It may be that typical instruction is better suited to definitional questions and content like Question 6 while the game is better at helping students reason about a process or apply concepts like in Question 7.

The depth ratings for Question 8 did show pretest sensitization effects.

The only significant effect on response length was a positive main effect at Time 3 for Question 7 ($t(5)=2.754, p<.05$). Students who received the game second tended to write longer responses about the scenario with the cougars and mountain goats.

Analysis of treatment effects on markers

Initially, the markers were analyzed in a similar manner to the MC scores and interest scale ratings except it used a Generalized Linear Model. However this analysis had trouble handling the low hit rates of some of the rarer markers. To address this, the analyses were redone using Fisher's Exact Tests to compare the proportion of students displaying the markers to those not displaying them between groups. These tests were done at Times 2 and 3 looking across all 4 groups and collapsing the groups to look for overall effects of either pretest presence or game order.

As with the depth data, the game's effects on the markers were very mixed. For Question 6, "Briefly describe what makes one organism 'more fit' than another, in the context of natural selection." significant changes were found in the 3 most common markers. At Time 2, students who had just received the game mentioned

reproducing significantly less (6%, $p < .001$) compared to the typical instruction group (36%). Looking across times, this was also significantly less than the same Game First group mentioned it after receiving typical instruction (36%, $p < .001$). It appears receiving the game first made students less likely to mention reproduction than students who received typical instruction but they recovered after also receiving typical instruction. Also at Time 2, students in the Pretest group who received the game module mentioned generally being 'better adapted' to an environment or than competitors less (25%, $p < .001$) compared to students who received typical instruction (80%). This may have indicated less superficial responses but no increases were seen in the other markers and these differences faded by Time 3 as well. It is unclear why there was pretest sensitization to this type of response.

At Time 3 the game was associated with to a different effect, with the Game Second students mentioning survival significantly more in their responses (71%, $p < .001$) compared to the Game First group (38%) at that time. This was also significantly more than the Game First group directly after completing the game module (34%, $p < .01$), showing the effect was an increase in the Game Second group's responses. Taken together, it appears that getting the game emphasized the role of survival in fitness. During Interval 1 it de-emphasized the importance of reproduction but this was recovered with typical instruction. During interval 2, for students who already had typical instruction on the role of reproduction, it instead made them more likely to mention survival as well.

Questions 7 asked students to reason about a selective pressure:

“A population of cougars (a type of large cat) have recently moved into the habitat of a population of mountain goats and have begun preying on the goats. Give an example of how this change may impact the population of mountain goats.

Beyond there being less goats, how might the population change?”

Here there are significant differences but they appear to be between groups rather than treatment effects. At Time 2 the Game First group referenced 'any traits that helped the goats survive' and 'goats passing on traits' significantly less (respectively 6%, $p < .05$ and 3%, $p < .05$) compared to the Game Second group that had typical instruction (29% and 24%). At Time 3, these differences persist with the Game First group still mentioning these markers less (6% 0%, $p < .05$ and 0%, $p < .01$) compared to the Game Second group (24% and 32%). It is possible this is an order effect but given the consistency in the response rates over time in each group it seems to be a group difference rather than a treatment effect.

Question 8 was perhaps the most open ended asking simply “For organisms that sexually reproduce, how do they select a mate?” and saw almost no significant differences. There was a significant effect at Time 2, where students in the Game First group mentioned some form of 'assessing a specific trait' significantly less (13%, $p < .01$) than the Game Second group (48%). This effect disappears at Time 3 when all groups displayed higher response rates (30-52%). The only other differences involved pretest effects. At Time 2 students in the Game First group that were pretested mentioned some form of 'a mate perceived as more fit' significantly less (13%, $p < .05$) compared to the Game Second group (48%). At Time 3 this marker then had an explicit pretest effect rather than an interaction, with students who were pretested mentioning the marker less (10%, $p < .001$) compared to students not pretested (44%).

There was also a completely novel short answer question that was added at Time 3 and asked to all students, to attempt to assess students' ability to apply evolutionary reasoning to novel problems. Responses to that item have not been analyzed at this time.

DISCUSSION

These results show that while the game module may provide some benefits under specific conditions, there are significant limitations to the effects and it can be difficult to test these effects in real world situations. The game module had positive effects, including multiple choice scores, deeper responses to a reasoning question, and increased interest in items closely related to the game module, but primarily for the Game Second students. It appears that to get the best results from this particular game and the materials around it, students needed some foundation in typical instruction. Without such preparation, the Game First students saw less benefit from the module and less benefit from subsequent typical instruction.

Limitations

Perhaps more than the results, the many limitations of these findings highlight the difficulties of doing this kind of work and obstacles that need to be addressed for future meta-analyses to provide more conclusive answers about the effectiveness of these types of video games in the classroom.

First, there were a number of major limitations based on the implementation of the design, specifically in the sample used, the way the treatments were administered, and the way the data was collected. In the limited time the study was collecting data, the teachers who volunteered to participate worked with a variety of students but there were simply not enough to provide useful analysis of differences in treatment effects between all groups. For example, there were not enough AP or non-AP students between treatment groups and there was only one class of 8th graders while the rest were 11-12th graders. There may have been important differences in responses based on these factors that this study was unable to address.

There are also issues of fidelity to the module and the research design. Teachers were recruited and contacted through email, so there was little direct supervision or available information about how they used the provided materials in the classroom. This was likely a factor in the compliance issues seen in some classes where it appears the assessment at some timepoints were simply not collected by the teacher, possibly due to miscommunication. Another consequence was a possible lack of fidelity in how the module was used. While no data was collected, informal comments from teachers implied that some teachers may have focused on having students complete the handouts while others did not. This kind of variability was also seen in the pilot and appears to be common practice by teachers adapting materials for their specific classes. If the module were being distributed as a free educational resource teachers would be using it in their classrooms with little guidance beyond the handout so this has some benefits in terms of ecological validity but at great cost in terms of findings. It speaks to the robustness of the effects found that they were significant across highly variable implementations of the game module and typical instruction but it limits possible discussions of how effective aspects of the module were for different classes. This was accounted for statistically as a random effect but there was no observational data about how classes differed to suggest specific possible mechanisms or future directions.

It should be noted here that this sample was also self-selected, though this is one of the less problematic aspects of the design. This study was seeking to test if this type of educational approach could produce effects, so putting it in the most favorable conditions is not inherently problematic. However the sample was drawn from teachers with enough interest in this approach to respond to recruitment notices and spend the time to prepare the module (often including scheduling time to work with IT staff). This indicates a level of investment that is likely relevant and may be a factor in

how these results generalize to other classrooms.

There was also the problem of the group differences in teacher ratings of student motivation. This provides a confounding variable as the motivation ratings were shown to affect MC scores, interact with game order, and were highest in the Game Second, No Pretest group that also saw the greatest MC benefits. These benefits may have then come from inherent motivational differences rather than treatment effects. However, even for the more motivationally comparable Pretest groups, the Game Second, Pretest group still showed better MC scores and gains compared to the Game First, Pretest group. This indicates that while the Game Second, No Pretest group may have seen additional benefits from its higher baseline motivation, setting it aside there were benefits from being in the Game Second group. This confound is still problematic and a notable limitation of the findings.

Beyond the implementation of the research design, the nature of the assessment has some further limitations. The multiple choice items were written to measure change in the concepts the game module was intended to address. While those concepts were based on public standards (the Next Generation Science Standards) and were expected to be covered during the typical instruction for each class, the game and multiple choice items were made to work together in a way the lessons during typical instruction were not. The variety of lessons the teachers used may have covered different amounts of other material which complicates comparing those lessons to the game module. The gains seen during typical instruction mitigate this concern somewhat but not entirely as the gains indicate that the lessons had similar effects and likely covered similar material to the game module.

There are also the inherent limitations of self-report interest scale items, though these have been explored in previous work and are merely acknowledged here.

There was also no follow-up with the students so while there were effects there

is no information on their persistence.

Finally there is the nature of the game itself. It strives to be accessible to all students but ultimately it attempts to present a rather elaborate model of evolutionary dynamics and their effects across generations. Many previous games have focused more on memorization of facts than trying to develop an intuitive understanding which may limit the how these findings generalize to the effects of other games and game-based lessons. The order effect seen here may be useful to consider for other similarly complex games but not all educational video games.

The fact that Cellvival is a computer game and the module is designed to work with each student playing on their own machine provides a final limitation. While technology access is improving, there are still a number of schools that would not be able to use the module due to lack of machines or trained staff that can setup the game on those machines.

Benefits and Implications

While there were many limitations, the results do provide a number of useful findings and suggest possible future benefits. With proper preparation, the game module saw greater gains than typical instruction in specific areas, including student motivation. While the motivational gains were very specific, these findings still support the idea that game-based lessons could be a way to address engagement problems in the classroom. At the same time, the positive effects on multiple choice items based on public standards show that game-based lessons can be effective tools even as standardized tests become more prevalent.

The need for preparation

The limits of these effects also provide useful information on the importance of

context and game type for future work on games-based learning. Even with a prepared module of materials to help situate the game in the curriculum, *Cellvival!* still needed to follow more instruction on the topic in order to have the most benefit. Other games developed based on similar principles and theories of learning will probably also see the greatest gains only after adequate preparation, though the specifics may differ. Games that are trying to model a complex dynamic system and scaffold student interactions with it to facilitate intuitive understandings of the principles behind that system need to familiarize the students with the terms and concepts to help them better make sense of that model. Games designed to introduce concepts or help memorize terms through repetition are unlikely to need this kind of setup. The findings here highlight its importance for this kind of game and can inform future similar efforts.

Similarly, the negative effects seen in the Game First groups provide valuable insight into the consequences of misusing games in the classroom. Even when designed from the ground up for classroom use, when not used appropriately a tool can have negative impacts. This work shows that in this case, presenting the game module with adequate prior instruction is an element of appropriate use. Games have great potential but are not a magic bullet. These findings show not only how to use this type of game to best effect but the potential consequences of using such games in other ways so others can avoid making similar mistakes.

Short answer responses

The short answer responses show another area where a game-based approach has potential benefits but must be used carefully. The greater depth gains on Question 7, which asked students to reason about a selective pressure, shows there are benefits of a game based approach for addressing this concept. It supports the idea that attempting to convey such concepts through gameplay may lead to deeper

understanding and better ability to apply concepts to solve problems.

At the same time, the decreased gains on Question 6, asking students to define fitness, highlights the limitations of this approach. It appears that typical instruction may be better in terms of students' ability to articulate definitions. That ability to express or articulate may be the driving factor here; while no multiple choice items explicitly asked about fitness, the concept was critical to many of them. In the results, the Game Second students had better MC scores after the game module but students who had had typical instruction but not the game module had the greatest gains in Question 6 depth. This suggests the game may have helped students understand fitness and select options but typical instruction may be better at getting them to produce good definitions, given an open ended prompt.

Even with this limitation, the gains in depth on Question 7 are exciting. Among the shifts there were some striking improvements: One student went from saying that "goats will travel away from the cougars" to "The goats that survive will pass on important traits to make offspring more capable of surviving cougars." after the game module. Seeing this shift from the superficial elements to the deeper structural factors of a problem was very encouraging and noted by teachers. It is exactly the kind of deeper understanding this more experiential form of instruction was intended to facilitate.

Motivational implications

While these results show that interest created by the game did not transfer, there were additional informal observations and reports of how engaged students were and how much they wanted to play the game more. In the pilot classrooms, the students were often very intensely invested in the survival of their cell and often vocally concerned when predators were nearby. During the evaluation there were also

reports of students either asking to play the game after class or coming back to the computer lab to play more after class. These kinds of behaviors, along with the gains on the motivational scales, strongly suggest that students were very engaged and motivated to continue playing the game. These kinds of responses contrast student responses to previous ‘edutainment games’, which were not enjoyed or pursued outside of class.

As previously discussed, *Cellvival!* was designed based on concepts from Self Determination and PENS theories of motivation. These theories provide a framework for how to design motivating games and describe why earlier less successful games were not motivating. These reports are consistent with the ideas that *Cellvival!* successfully applied these theories in order to facilitate player motivation to play and that these theories can be applied to make more motivating game designs (or describe why some games fail to motivate players).

Implementation challenges

As discussed under limitations, there were significant implementation challenges to doing this work and that complicated interpreting the findings. This is likely a factor in why more work on this topic is not done and hopefully information about this process can be useful to future researchers.

Classroom access

The biggest obstacle is simply getting into classrooms. There is a need for administrator approval, IT support, and teacher’s time that are all in short supply in public schools. The key for *Cellvival!* to address this was building strong connections with the teachers and this is where the partnership with ASSET was invaluable. As an established program that had run teacher workshops and distributed quality lab content for years (and was associated with Cornell University), ASSET had a reputation for

providing quality content and good support to teachers. Presenting the game as new content for the ASSET curriculum helped tap into an existing network of teachers and highlight how the game would work with activities they were already using in their classes.

Once teachers became interested in the module, they become the best advocates for addressing these obstacles at their own schools. Once the teachers buy in, they can use their contextual knowledge to help get the other resources to make this happen for their classrooms, either setting up lab time, IT support, administrator approvals, or putting researchers in touch with the appropriate contacts. In addition to the reputation, this 'buy-in' was supported by sending the module materials and game early in the process, so they could become familiar with the material or make a more informed decision if they wanted to use it. Many teachers are actively looking for ways to engage students and want to use video games but aren't sure how; a document explaining how this is intended to increase engagement and then giving an in depth manual about the games was greatly appreciated. One common request was a video walk through of playing the game but this was outside the scope of the project.

There is a technical obstacle to be noted that most public schools have older computers with a variety of operating systems, so any game must be compatible with that variety of environments. This took some additional development time to address.

Sampling and fidelity

Once the teachers are committed and the game is successfully installed on the computers students will use, issues of sampling and fidelity can become apparent. Some of the sampling issues that limited this study arose from restricting the sample to one state during a one semester period. ASSET primarily operates in New York State and there were concerns about different standards across states. There were also other teachers that were willing to participate but not until the spring term or later. Having a

longer data collection period is a simple way of increasing sample size.

As previously mentioned, distributing the materials and collecting responses online greatly increased the geographic area that could be covered at the cost of direct classroom observation and oversight. In the pilot, a researcher was actually in the classroom each time the module was used and collected paper surveys. These observations provided some idea of the variation between teachers. One teacher in the pilot even hadn't played the game before the first day of the module, then did between days and was much better at handling questions and discussion the second day. There was also the difference in the use of handouts and time spent on discussion. This kind of information is important for refining the module and interpreting the data, but the resources were not available to 'scale up' this approach. Putting the assessments online also made them easier for teachers to administer, as students were already in a computer lab and they were automatically transmitted to researchers.

A good middle ground for future work might be to recruit teachers online and distribute materials electronically while also observing a subset of them. While it may be difficult to be in all classrooms, observing some would be useful to have some estimate of variability and information about different practices.

It is also important to remain closely in contact with teachers in the lead up to and during the module. Teachers tend to be very busy and even committed teachers may find it difficult to make time to prepare before the module and keep track of the assessments, especially if they have classes in multiple conditions. Keeping in touch can help make sure they keep the module in mind and make sure they are ready for it. Another benefit of the online assessments also make it easier for the researcher to make sure the proper assessments are being done and contact the teacher to quickly address any problems.

Finally, a key way to address sample and teacher familiarity would be repeated trials. If teachers did the module over multiple years, not only would there be more students but some of the noise caused by differences in familiarity during the first session could be addressed.

Game production

Apart from the mechanics of the research, another major obstacle is initial production of this type of game. Even the design of the game, setting aside programming, art, and sound, requires bringing together expertise and skills in game design, education, and the content of interest. More importantly, it requires not just bring these skill sets together but making sure they are each respected and applied appropriately.

For example, educators or other content experts will often suggest or even insist a game should include mandatory quizzes or questions players must complete to continue “to ensure students are learning and not just playing the game”. However, that would very likely decrease student engagement with the game; deep integration of the content addresses this same concern in a better way. By carefully integrating the content, that distinction between “just playing” and “learning” can be reduced if not avoided. Further, if the game well integrates the content, it could be argued that including such interruptions would actually make the game less effective educationally, by decreasing engagement.

On the other hand, those more versed in traditional game design may suggest mechanics, such as random temporary “powerups”, that may make the game more fun. However, if they correspond to nothing in the content of interest and are only suggested because “this kind of game tends to have them” their inclusion may also interfere with the message the game it is trying to convey. Any potential gains in engagement may not be worth the loss of accuracy to source material and confusion in

students.

It takes a clear goal and good communication among a team to make sure the right decisions are made, everyone on the team understands why they are made, and everyone remains invested in the project. Otherwise, it is difficult to balance the various concerns, such as player engagement and accuracy to source content, that go into an effective educational game. Beyond gathering a team with all the needed skills, ensuring the team maintains the proper balance to produce the most effective game is an ongoing challenge of this kind of game production.

Further Work

This work provides needed data on the effectiveness of deeply designed educational games in a classroom context, though its usefulness is hampered by numerous sampling and fidelity limitations. The most basic need is simply for more high quality data on games in classroom settings. There are significant barriers to access student and teacher populations as well as to develop these kinds of games. It takes the partnership of educators, administrators, designers, programmers, artists, content experts, and researchers for these kinds of evaluations to be successful, making it more difficult. However, more of these projects will be needed for the literature to provide conclusive findings.

Among such efforts it is also important that the effectiveness of games is evaluated across a number of topics and contexts. The learning principles discussed and applied here would be expected to hold across topics from science to history etc. but such theories need to be empirically tested.

Similarly it should be tested for a variety of students and teachers. The students in this sample were from a mix of lower level classes up to AP Biology from different towns but a number of other possible factors were not specifically tracked such as

SES, past academic performance, or cultural background. Similarly the teachers' typical instructional styles, classroom environments, and school cultures were not examined. These kinds of factors may moderate the effectiveness of games-based educational approaches and inform how to best use such approaches. Some of the motivational outcomes here, showing students that initially rated themselves having low interest then had the greatest gains, suggest that such approaches could be effective at helping those populations underserved by current approaches.

Apart from further replications and testing the generalizability of these results, there is also work to be done delving deeper into the mechanisms behind these effects. Beyond coarsely testing the effectiveness of a game compared to typical instruction there is a need for evaluations of different versions of the same game with theoretically grounded differences in their mechanics. Testing the effects of an elaborated model and system such as *Cellvival!* compared to a game focusing on one aspect of evolution, for example; would the more focused game help students better understand and remember that aspect or do they benefit more from contextualizing it in a larger system? These kinds of empirical questions about how to design more effective educational games are a logical step after determining simply if they are effective.

Finally, this also extends to the materials and context around such games. Given a game suited to a particular topic, how does one best use it in the classroom? Building on the findings here: Can a teacher use a simpler game to introduce concepts and generate interest, then lead some instruction to build on that experience, and finally use a more complicated game to refine students' understanding? Are cycles of discussion and play the most effective way to facilitate reflection and transfer or are other ways better? And then how does the effectiveness of different approaches vary across classroom contexts and students? In the broad view, work needs to be done to

better understand how to make and use these kinds of materials and the factors that influence their effectiveness.

Conclusion

For all the promise games have, rigorous research is needed to establish the benefits games can have in classrooms and explore how to strengthen and spread those benefits to students who need them. This study attempted to address that need for data and though it has limited generalizability these findings do provide some support for the benefits of carefully designed games and emphasize the importance of context. As with non-game lessons, the effects of the lesson are dependent on the lessons that came before and affect the lessons that come after.

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APPENDIX A

Overview of Gameplay and Design

In *Cellvival*, the player controls a series of *Tetrahymena* cells with the goal of getting their cell line to survive as long as possible. The game can be thought of as having two levels of play: the moment-to-moment play of controlling a single cell and the more long term, strategic play of reproduction. Most of the time the player is controlling a single *Tetrahymena* cell attempting to survive by avoiding predators and gathering enough food to reproduce. Once the player has gathered enough food, they make choices that can increase their population and/or alter the traits of the next generation. The player is then given control of a cell from the new generation and again attempts to survive and gather enough food to reproduce. This creates a cycle of trying to survive, making reproductive choices that enable the next generation to survive more easily, and then playing as the next generation. This structure was designed to balance the goals of meeting the learning objectives, engaging players, and allowing player-driven exploration and experimentation.

This design can address a number of learning objectives. By controlling a cell each generation, players can see how changes across generations can make it easier or more difficult to survive in a given environment. It scaffolds considering how selective pressures affect a specific population at this point in time as well as how such pressures change a population over generations. This allows players to experience a model of selective pressures in a different way. The goal of survival is consistent with the goal of actual organisms and pursuing it makes learning about the environment, and how to survive there, more important for the player.

To maintain engagement across these iterations, the single cell gameplay is very straightforward and intuitive but the reproductive gameplay adds more depth and options. This helps make the game accessible to new players but then offers new

challenges to maintain engagement in more advanced players. The single cell gameplay offers immediate feedback, such as getting eaten or getting food, in response to player actions which makes consequences clear, provides a sense of agency and helps players develop a sense of mastery as their skill develops. Based on the Player Experience of Need Satisfaction (PENS) model of player motivation, this should help fulfill player's needs and increase their engagement and likelihood of continuing to play the game. Similarly, their reproductive choices have meaningful consequences to their survival as a single cell, providing more feedback and agency.

Finally, this structure allows the player explore both the physical space of the environment and the possibility space of potential cells. The environments are semi-randomly generated so they will not be laid out the same way twice. This keeps the layouts of obstacles, food, and hazards from becoming repetitive. The player can discover rewarding high food areas or dangerous groups of predators for themselves. In the possibility space, players start each session of the game with a balanced cell and as they reproduce each generation can change its traits incrementally. This allows the player to experiment with different sets of traits and figure out if they seems to make it easier or more difficult to survive in the current environment.

Features of Single Cell Gameplay

Movement controls and avatar

The game is entirely controlled with the mouse and only one button is used to control the cell's movement. This was done to make the game as easy to use as possible so it was accessible to the widest number of students. The camera is also always centered on the player controlled cell requiring no additional controls.

The player controlled *Tetrahymena* cell was designed to balance engagement and accuracy. The artificial coloring makes it very easy to see against the game's

background and the design is eye-catching (Figure A1) while still being recognizable when students see live *Tetrahymena* under a microscope. The cellular avatar also features cilia, as the actual cell does, but these are more visibly tied to movement. While actual *Tetrahymena* move their cilia too fast to perceive the in-game cell slows the motion down and ties their speed to the cells' current movement speed; this correlation helps make it clear to the player the cell is using them to move. Finally, like in real life, the in-game *Tetrahymena* have an “oral apparatus” or mouth. Including this in the game slightly increases the challenge of feeding for players, makes them be more aware of their positioning to feed successfully, and makes it very clear how *Tetrahymena* feed.



Figure A1: Screenshot of single cell gameplay

Predators

There are three kinds of predators each with different behaviors and based on actual predators of *Tetrahymena*. Heliozoans or “sun animals” are round and surrounded by spike-like pseudopods (Figure A2, A). They are very slow moving but if any part of them touches a *Tetrahymena* cell, they will pull it toward their central

mouth and devour it. Euplotes are free swimming and will chase *Tetrahymena* they encounter (Figure A2, B). However they have to get the prey into their mouth in order to eat it. Finally, there are the much larger Cyclops. While Heliozoans and Euplotes are about 3 times as large as a *Tetrahymena* cell, Cyclops are approximately one thousand times larger (Figure A2, C) and somewhat faster than *Tetrahymena*. They do not fit on the player's screen as they swim through it. Being so much larger, they do not pursue *Tetrahymena* but filter feed on any smaller cells that go into its mouth. They also push the normally immobile obstacles out of the way as they pass, reshaping the level as they go. These three provide a variety of challenges to player survival.

These predators were selected for the game due to their different feeding behaviors and distinctive appearances. Avoiding being eaten by the mobile Euplotes often requires different actions than the prickly Heliozoan. These organisms are more memorable to the students due to the threat they pose to the student's progress in the game. The Cyclops is particularly memorable for the way it will fill the screen and alter the environment as it swims by. The predators implicitly remind players that there are larger things in a *tetrahymena*'s environment and a variety of other organisms, even at the microscopic scales.

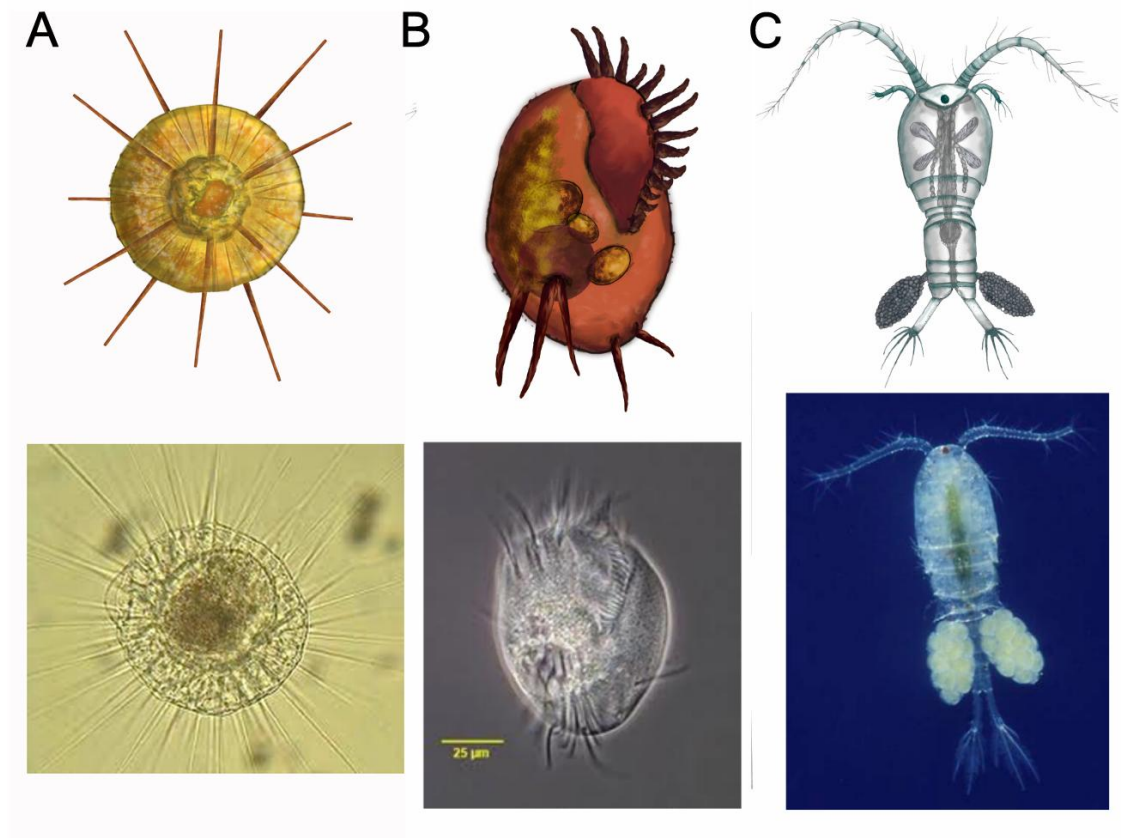


Figure A2: Predators used in *Cellvival*

The upper row shows the in game appearance, while the bottom row shows micrographs of the real world organisms.

Hazards

In addition to predators and immobile obstacles there are also two types of hazards in the game. One type simply slows down any cells that pass through it. The other interferes with the player's control, redirecting the cell's movement away from the cursor erratically. These hazards are based on substances a *Tetrahymena* might encounter such as a high viscosity substance that would slow it or any number of toxins that interfere with ciliary action (which the cell uses to swim). While these hazard areas can be problematic they also provide opportunities to the player: Predators like Euplotes will try to avoid entering them so sometimes they can be used

to escape.

The hazards add more variety to the levels and a different kind of pressure than the predators. While predators may devour the player, hazards merely make it more challenging to obtain food. This dynamic is more discussed when making reproductive choices

Food bacteria

The food bacteria are the one positive element moving about the environment of the game. They are much smaller and slower than the *Tetrahymena* and will feebly attempt to avoid the predation. However it is worth noting that the other predators can also consume these smaller prey so often the player must be careful about their approach in order to eat the food bacteria without being eaten by others.

Labelling and the codex

Every element in the single-cell gameplay, from the predators to the hazards to the obstacles, has a mouse-over name and codex entry attached to it. This means that whenever the player moves their mouse cursor over something in the environment, its name will be displayed at the top of the screen along with a prompt that they can right click for more information. If the player right clicks on the element, the game will pause and open the appropriate codex entry. In addition to a micrograph, these entries provide clear information about how the entity functions in the game and a fun or interesting facts about them in the real world. For example, the entry for Euplotes describes how it can use rows of fused cilia to walk along a surface along with a picture of it doing so.

This system serves multiple functions. Since the name is displayed every time something is moused over, it is readily available and repeated so it can help students

learn the names of organisms through repetition and exposure. Secondly, the codex entries attempt to scaffold connections between the game world and the real world. Finally, by making it as easy as possible to find more information about the organisms and objects in the game and then making the information rewarding the codex attempts to encourage further information seeking. It attempts to motivate students to learn more about what is happening in the game even outside of class. This is why there is both information that is useful to pursuing player's goals within the game (to provide immediate benefits) and information that may be interesting or surprising (to encourage further exploration).

Interface

As the player is searching the level for food and attempting to avoid being eaten, the interface provides useful information and access to other features. Primarily, the upper left displays a 'food meter' that measures how much more food is needed in order to reproduce. Once it has filled, a "Reproduce" button appears next to it prompting the player to enter the reproduction interface and create a new generation.

Features of Reproduction Gameplay

This interface (Figure A3) provides players with a number of decisions and information to inform those decisions. It allows players to choose whether to sexually or asexually reproduce and to choose a mate if they are sexually reproducing. It also displays the traits of the previous generations of the player's cell and the traits of possible mates through the cell history graphs that dominate the interface.

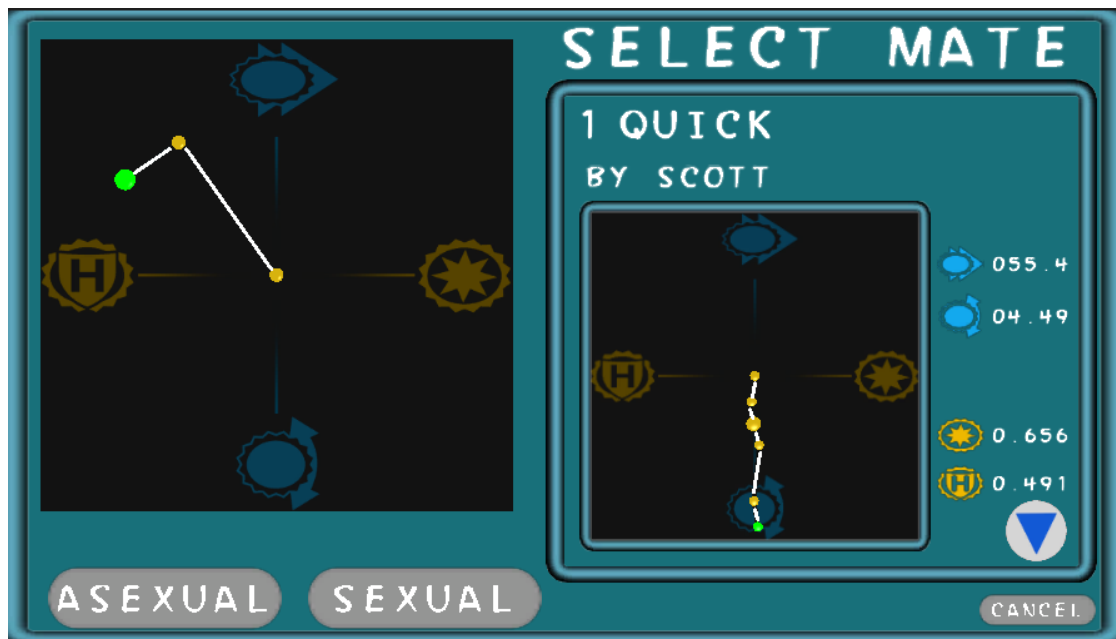


Figure A3: The reproduction interface

Cell history graphs

The cell history graphs allow the player to visualize the change in a cell line across generations. They do this by graphing the traits of the cell. In *Cellvival*, *Tetrahymena* cells have four traits: move speed, maneuverability (or turn speed), metabolism (of how much energy the cell gets from each unit of food), and hazard resistance. These four traits all directly impact the basic gameplay, making it easier or more difficult to survive and reproduce frequently. They are also grouped into opposing pairs; if a cell increases its move speed, it decreases its maneuverability and vice versa. This pair of traits can form a line or axis that the cell moves along when its traits change. Since there are two pairs, a two dimensional space can be defined that describes all possible sets of traits a cell could have and the cell's current traits define a point in that space. When a new generation is produced and traits change, this new cell defines a new point and a line can be drawn showing the change and connecting

each subsequent generation. This is what the cell history graphs display; a line that shows how the cell's traits have changed each generation as well as the traits of the current cell.

The reproduction interface

The reproduction interface is designed to use the cell history graphs to provide information about past choices, their outcomes, and potential choices, so the player can make informed, meaningful decisions. The cell history graph on the left shows the history of the player cell. This allows the player to see what traits they have had in the past and recall their own experiences of playing as that cell; it can help them reflect if that set of traits was helpful or not in the current environment before making the current reproductive choices. The graph on the right shows the history of a potential mate. This includes the traits of the current generation which will influence the offspring if that potential mate is selected for breeding. The player may browse through multiple potential mates using the arrows (Figure A3) then use the buttons at the bottom to choose whether to asexually reproduce or sexually reproduce with the currently displayed potential mate.

The tradeoff between sexual reproduction and asexual reproduction, as in actual *Tetrahymena*, is that sexual reproduction allows for greater change in traits while asexual reproduction increases your population more quickly. What changes do occur in asexual reproduction are also largely random. In game, changing traits and increasing the population are both beneficial for survival, which is why getting enough food to reproduce is central to the gameplay. However the scope of these effects is moderated in the game; while real *Tetrahymena* produce orders of magnitude more offspring in the same period through asexual reproduction, in game, asexual reproduction produces one additional offspring. Sexual reproduction produces only the

new cell the player takes control of. The size of the population is tracked and displayed to the player.

The population system and display

In the left corner of the basic gameplay interface (Figure A1) is the population monitor. If the cell the player is controlling dies but there are other members of the population, then the player will be given control of one of the survivors. If the player's cell is the last member of the population, when it dies the cell line is extinct and the player must start the level over. Starting over means beginning the level again with the balanced cell that is not particularly suited to any environment and thus losing all progress. This means a large population will help a player's line survive longer.

The interplay of the population and traits creates interesting choices for the player and is intended to incentivize behavior similar to actual *Tetrahymena*. Since it produces offspring so much more quickly, *Tetrahymena* will normally reproduce asexually as much as possible and only resort to sexual reproduction when they are starving or conditions are otherwise adverse. This allows them to then attempt to adapt to these conditions. In game, it can be advantageous to sexually reproduce until it is easier to deal with the environment then asexually reproduce to increase your population and have more insurance against random events. This is not explained explicitly but arises from the dynamics of the system.

Additional systems: level selection and generation

There are two environments, or levels, available in *Cellvival*. They are not intended as a difficulty progression but to favor different sets of traits. One environment has scarce food and lots of obstacles but few hazards; this makes building speed difficult and hazard resistance unattractive thus making higher maneuverability

and metabolism attractive. In contrast, the other environment features lots of food and hazards with few obstacles; this makes speed and hazard resistance attractive. Again, these differences are intentional but not explicitly communicated to the players. The intent is for them to explore combinations of traits and find what works best on their own. Then they can try the other environment and find that a different environment can favor different traits even making the traits that were favored disadvantageous.

While the proportion of various objects in each environment is controlled, the specific numbers and placement of those objects randomly generated each time the environment is loaded. This semi-random generation increases replayability of the game and provides new opportunities for exploration with each playthrough. Additionally, the large predator does reshape the level to an extent by pushing obstacles out of its way as it swims through the environment. This provides some degree of variability even within a playthrough.

APPENDIX B

Game Production and Design

Initial design work

I initially met with staff from the ASSET program and reviewed their lab modules to design a game that would fit well in their curriculum. After reviewing the material, an initial design that included navigating the environment, gathering food to reproduce, and reproducing allowing movement through the ‘genespace’ that described possible cells was quickly sketched out. I then met with Walker White repeatedly between September 2011 and December 2011 to refine the design and discuss ideas. During this period, the traits and their pairings were defined, ideas for unlockable rewards were considered, the in-game food economy was defined, and possible predators and hazards were generated. Further meetings with ASSET during this time also helped match design goals with educational content, such as which predators of *Tetrahymena* have feeding behaviors that would produce engaging gameplay.

Game production

Between February 2012 and August 2014, I worked with a series of programmers and artists to develop the game. As I had little programming experience, I worked as the designer and project lead. I was most involved in decisions impacting the user experience, such as the form of interfaces, controls, tutorials, and difficulty level. Later, when I was running playtests and pilots I was also taking that feedback and working with the team to respond effectively. Throughout the process I organized the team, set priorities, and managed the production, particularly when playtest or pilot dates were approaching.

Typically the current team had weekly meetings where each member would

update everyone on what they had been working on, their progress, and any difficulties they had encountered. These updates would be discussed and then I would set priorities and tasks for the next week. When new members joined the team, I would bring fill them in on the goals and design of the game and then the current programmers would familiarize them with the more technical details of the project.

From February 2012 to June 2012, the initial team consisted of Erica Shuyan, John Decorato, and Aleksey Polesskiy. As Aleksey was already familiar with Unity he became the lead programmer. During this period, the focus was on implementing basic gameplay and systems for player controls, movement, eating food, and hazards were implemented.

From June 2012- September 2012, the team was reduced to only Aleksey, but he managed to implement many more of the core systems of the game during this period. These included the reproductive system (the underlying mechanics, as the interface was still in progress), the ‘genespace’ or ‘cell history’ display, the ‘spinner’ selector for asexual reproduction, a simple predator AI, a new GUI, additional reproduction functionality, and the population system. That is, the code for generating extra offspring when reproducing, transferring player control on cell death, and controlling the NPC *Tetrahymena* population.

It is worth noting this population system was not part of the original design. I had discussed with the previous team the conditions under which *Tetrahymena* asexually and sexually reproduce and as the reproduction systems were implemented, Aleksey suggested a way to create a game mechanic around this distinction. We worked together to develop the idea into the population system that was implemented. It added more depth to the game and modeled additional aspects of reproductive choices in a way that was more engaging and educational.

From September 2012 – December 2012, Scott Warren and Lauren Cruvellier

joined Aleksey. Scott assisted Aleksey with coding and implemented refinements to the reproduction GUI, the system for saving and loading cells, the large predator, and that predator's ability to knock around obstacles. Lauren worked as an artist and animator and after we established a style and I provided her with biological references, she contributed the *Tetrahymena* model and the animations for the swimming food bacteria.

From January 2013- June 2013, Scott left the team while Timothy O'Brien, Derek Chiang, and Jessica Roth joined. Jessica was also an artist and developed assets for the interface and predators. Derek worked on a server/client system that was not included in the final game. Timothy worked on the menu system, level selection, and tutorial level. Lauren contributed a swimming animation for the *Tetrahymena*. Aleksey became occupied with other projects and helped familiarize Timothy with the code.

From June 2013-September 2013, the team was reduced to Timothy and Jessica who were joined by Fernando Ito Tadao. Timothy and Tadao worked on further developing the GUI, random level generation, and the 'codex' or in game reference and help file. I generated the entries with oversight from ASSET staff. Jessica worked on more assets for predators, including one based on high school student art, and in game text.

From September 2013- December 2013, Ryan Pindulic joined the team, and a pilot playtest in a classroom was performed which found compatibility issues with the older machines common in public schools. Much of this period was spent optimizing performance while polishing the interface and user experience.

Ryan took over as the only other team member then until the beginning of the study, continuing to polish the game and address bugs found in playtesting.

APPENDIX C

Game Module Teacher Handout

ASSET: Pilot Lab

Advancing Secondary Science Education through *Tetrahymena*

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Cell-vival, featuring *Tetrahymena* (High School)

Authors:	Andrew Jefferson, Cornell University
Appropriate Level:	This lab is appropriate for students with basic computer skills. It would work well with high school level students.
Abstract:	Students play and discuss a game simulating the survival and evolution of <i>Tetrahymena</i> . They complete a worksheet to focus their attention, and provide information for classroom discussions.
Time Required:	For most students, this lab requires two 40-minute periods.
Special Needs:	This activity requires a computer for each student, and one for the teacher. The game should be installed and networked on the computers before running the activity.
National Science Standards:	LS4.B: Natural Selection, LS4.C: Adaptation

Cell-vival Game: TEACHER PROTOCOL

Quick Reference	Gameplay details	Page 5
	Lesson plan: Day 1	Page 8
	Lesson plan: Day 2	Page 13

Background Information

In this game, students play as a *Tetrahymena* in its ecosystem. They can control its actions, decide when it reproduces, and choose which of its potential offspring to control next (with the pretense that within the population all the possible offspring are produced somewhere). While playing students will encounter predators, prey and obstacles for *Tetrahymena*, all scaled appropriately.

Tetrahymena thermophila is a small ciliate that typically lives in freshwater systems and eats bacteria and small organic particles. It is predated on by a number of larger protozoans, rotifers, and even copepods, some up to 100 times larger than a *Tetrahymena*.

Why a video game?

This lab uses a specially designed video game to look at natural selection and how *Tetrahymena* interact with their environment. By creating a virtual world for students to interact with and learn from, we can let students explore the world in their own way at their own pace. This means a game can allow student to experiment with systems in ways that are difficult in the real world. A game can also highlight important information to students as it becomes relevant to them, and present that information in new ways. Finally, presenting information in the context of a game can be motivating and can draw student interest. It can also be more familiar and comfortable, as many students play video games.

Here a video game approach is used to help students become familiar with evolution and natural selection through experience and trial and error. They can make choices about how an organism responds to the environment and see how those choices affect its survival. A game lets them do this in a very direct engaging way, highlighting the consequences of their actions, and letting them do so over a large number of generations and conditions.

Terminology

Trait

A trait is an observable characteristic of an organism, like hair color, or mouth size.

In this game, you are only interested in heritable traits, those that can be passed on from one generation to the next.

Genetic variation

Genetic variation refers to the differences in the heritable traits of a group of organisms.

Even in a group of organisms that all look very much alike, like the dandelions in your lawn, there are small differences

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(variations) in genetic information. Aside from identical twins, no group of organisms is ever completely identical. These variations may make an organism more (or less) likely to survive and produce healthy offspring when the environment changes.

Environment

The environment consists of external surroundings including all of the living (e.g. animals and plants) and nonliving (e.g. terrain and energy) factors that surround and affect the survival and development of an organism or population.

Evolution

Evolution is the change in traits of a population of organisms over time.

Evolution can happen through 3 processes:

1. **Mutation:** General term for changes in an organism's hereditary information. Mutations can occur for a number of reasons, and create new genetic variations.
2. **Genetic drift:** Random change in the genetic variation of a population from generation to generation. It often occurs in traits that are not under selective pressure.
3. **Natural selection:** The non-random and gradual process of natural variation by which observable traits, including physiology and behaviors, become more or less common in a population.

Natural selection

In natural selection, variations that increase an organism's chances of survival and reproduction and are heritable (can be passed on to offspring) become more common in a population from generation to generation. Natural selection often drives evolution. Natural selection favors traits that improve fertility, speed up development, and make mating more successful – anything that improves the chances of producing healthy offspring.

In order for natural selection to occur, a population must have:

1. **Variation.** Organisms show individual variation in appearance and/or behavior. These variations may involve body size, hair color, facial markings, mating behavior, feeding behavior, or number of offspring. Some variation may not be observable, but may become important if environmental conditions change.
2. **Inheritance.** Some traits are consistently passed on from parent to offspring. These traits, such as number of fingers or blood type are heritable. Other traits are strongly influenced by environmental conditions and are non-heritable, like the ability to speak Spanish or ride a bike.
3. **High rate of population growth.** Most populations have more

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offspring each year than local resources can support leading to a struggle for resources. Because there are limited resources, many individuals die.

4. **Differential survival and reproduction.** Individuals possessing traits that make them better at competing for limited local resources (such as food, shelter, or mates) will contribute more offspring to the next generation.

Fitness

Fitness is the ability of an organism to both survive and reproduce. The higher the fitness of an organism, the more likely it will have many surviving offspring.

Predator

A predator is an organism that feeds on another organism.

Prey

A prey is an organism eaten by other organisms.

Selective pressure

Selective pressure occurs when something in the environment makes one organism more able to reproduce than another. For example, when you take an antibiotic to treat an infection, bacteria that aren't resistant to the antibiotic die and have no more offspring. If there were genetic variants in the original population that are resistant to the antibiotic, they will begin to reproduce and take advantage of the resources that they previously had to share. They will produce many offspring and after a few generations, nearly all the bacteria in the population will be resistant. In this case, the antibiotic exerts a selective pressure on the original bacterial population. Because the selective pressure was very strong, the inherited trait (antibiotic resistance) quickly spread throughout the population.

Adaptation

Adaptation is the evolutionary process in which a species becomes better able to live in its habitat. For example, birds that eat insects have long thin beaks, while those that eat seeds have short powerful, seed-crushing beaks.

Co-evolution

Co-evolution occurs when a change in the genetic composition of one species (or group) prompts a genetic change in another. Often this change prompts another change in the first species, forming cycle. For example, flowers and pollinators like bees and hummingbirds have co-evolved.

Coevolution is likely to happen when different species have close ecological interactions with one another. Examples of such ecological relationships include:

1. **Predator/prey and parasite/host relationships:** One species

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uses and harms the other to improve its own survival. For example, a hawk eating mice.

2. **Competitive species:** Two species that compete for the same resources. For example, lions and cheetahs both hunt other mammals in the same area.
3. **Mutualistic species:** Two species that both benefit from a relationship. One example is flowers and bees: flowers produce nectar that feeds bees, while bees transfer pollen so the flowers can reproduce. Another would be cows and their gut bacterial: the cow provides a safe environment (its stomach) and food for the bacteria, and the bacteria break down the cellulose in the grass into things the cow can digest.

Sexual Reproduction

Sexual reproduction is a process that creates a new organism by combining half the genetic material of two parent organisms. Genetic variation is caused by independent assortment of genes and crossing over during meiosis. Mutation may also occur during this process if the mutation occurs in the parent cells that produce the gametes.

Asexual Reproduction

Asexual reproduction, or cloning, is a process by which offspring arise from a single parent, and inherit the identical genes of the parent. This means that the only source of variation from the parent's traits is random mutation.

Mitosis

A form of cell division in which one cell creates two genetically identical "daughter" cells. For single-celled organisms, a form of asexual reproduction.

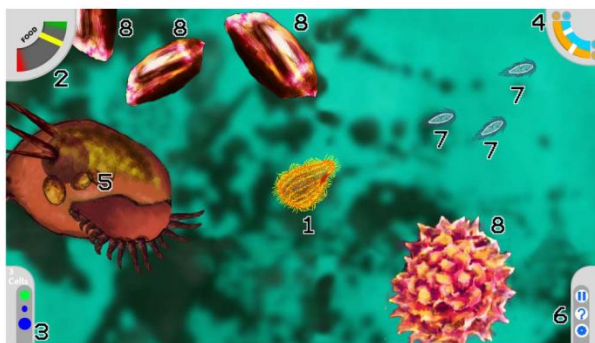
Meiosis

A more complicated form of cell division, in which one cell becomes four gamete cells, each with half the genetic information of the original cell. These gametes are then used for sexual reproduction in multi-cellular organisms, with gametes from two parents forming a complete set of information for the offspring. In single-celled organisms, other, more complex processes are used to allow for sexual reproduction.

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Details about Gameplay

The game is entirely controlled with the mouse. The player controls the cell in the middle of the screen, and when you click anywhere on the game screen, the cell will attempt to swim towards the cursor. The game will look like the figure below (without the arrows).



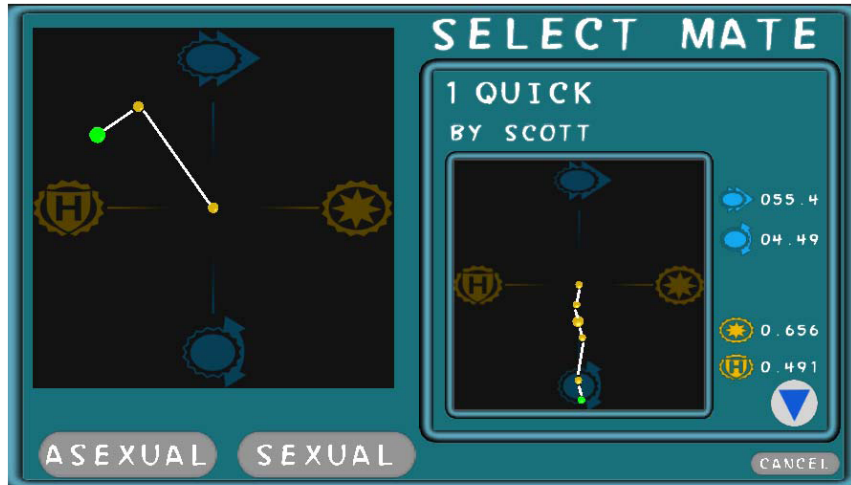
1. The player controls the *Tetrahymena* cell.
2. Food meter. This fills up as you eat bacteria.
3. The population monitor. This tells you how many cells are in your current generation, and the size of each cell tells you how much food each one has (ie. in this picture, the cell represented by the green circle has more food than the cell represented by the blue one). You are the bright green one.
4. Trait monitor. This shows your traits, which you can affect by reproducing.
5. This is a predator. Try not to get close and get eaten.
6. The pause and options buttons.
7. Bacteria. You can eat these
8. Obstacles.

The goal of the game is to survive as long as possible. Eating enough food will allow you to reproduce, and adapt to your environment. When you have enough food, a “REPRODUCE” button will appear next to the food meter.

When you click reproduce, it will bring up the reproduction interface. On the left is the history of your cell. It has 4 traits, organized in 2 pairs: speed/maneuverability and hazard resistance/metabolism. Speed and maneuverability are fairly self explanatory (maneuverability mostly affecting turn speed). Hazard resistance moderates the effect of harmful substances, for example allowing the cell to tolerate contact with a lethal substance longer so it's easier to

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escape. Metabolism affects how much food you get for each bacteria you consume. These traits are in opposing pairs, so the higher your speed, the less maneuverable you are, and the longer you can tolerate hazards, the less food you get from prey.



In the graphs, these pairs of traits are used as axis, so the cell's traits define a point. A line can show how traits changed between points. For example, in the graph on the left, the cell started in the center with all the traits balanced, then moved up (showing it became faster) and slightly to the left (gaining hazard resistance), then it changed again becoming slightly slower and gaining more hazard resistance. Each point indicates the traits of a new generation, and the graph lets you quickly see how the cell has changed over time.

The reproduction interface gives you a choice of sexual or asexual reproduction. If you asexually reproduce, you cannot change your traits as much, but any other cells with enough food will divide with you, giving you a larger population. If you die, you will swap to one of these other cells, so a bigger population can help you survive longer. If you sexually reproduce, you can change your traits by more, but will count as starting a new population; the rest of the current population will not be available if you die, making you more vulnerable (if you have no cells left, you restart the level). You select your mate from the other available cells on the right. You can see the full histories of potential mates and their current traits, which will affect your offspring.

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Note: Starting a new population with sexual reproduction is how the game represents the difference in reproduction rates. In the real world, sexual reproduction takes more time and energy and yields fewer offspring compared to asexual reproduction. In the game, effectively losing all the current cells is intended to make the distinction very noticeable, and encourage players to sexually reproduce only when they really need to or the population is already small, much as *Tetrahymena* actually do.

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Example Lesson Plan for Two 40 Minute Periods

Objective	This lesson plan is intended to help students appreciate how selective pressures affect reproductive fitness, how changes over a number of generations can accumulate, and how different environments favor different traits. It also introduces the game Cell-vival as a tool for further discussion and covering further topics, such as feeding behaviors and the effects of various toxins.
Materials List for a Class of 24	<ul style="list-style-type: none">• 24 computers with Cell-vival installed• Handouts for the students (Discussion day 1, Homework day1, Log and Discussion day 2, Homework day 2)
Preparation	It is highly recommended that instructors familiarize themselves with the specific level of the game that will be covered for that day prior to the class. After reading the background information, try playing the tutorial level yourself before showing it to students; read the in-game guides and included manual if any questions or concerns arise.
<u>Class period 1</u>	<i>NOTE:</i> The first level of the game has many hazards, few obstacles, some predators and plenty of food. Expect students to favor high speed and high hazard resistance to best be able deal with the environment, evade predators, and explore the level.
Objectives for students:	<ul style="list-style-type: none">• Create interest in the Microbiological world of <i>Tetrahymena</i>• Familiarize themselves with the controls and possible actions within the game• Learn how to read and interpret the cell history graphs• Have students reflect on themes/concepts in the game and tie it to real world situations
Introduction (~5 minutes)	<p>[The goal is to get students thinking about how the game relates to other Biology content]</p> <p>Show picture of <i>Tetrahymena</i> on the overhead or project it from the computer. Have students identify characteristics of the <i>Tetrahymena</i>. What do you think this is? Do you see a cilia, nucleus, etc.? Where do you think it lives? What do you think life is like as a <i>Tetrahymena</i>? What sort of challenges does it face? How do they deal with them?</p>
Initial Play Session (~15 minutes)	<p>[The goal is for students to get used to the game, and begin exploring it on their own]</p> <p>With each student at a computer with the game loaded, have students start and play through the brief tutorial and then the first</p>

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level (1-Stillwaterpond).

If students are initially confused about controls, try telling them to (left for PCs) click the mouse and see how the cell follows it. If they have questions about what something in the game is, suggest they click on it (or pause the game and click on it); this will open an entry giving them more information about the object or organism within the game and in the real world.

Allow the students time to explore the game and reproduce a few times to see how the change in traits affects how the cell responds and how it can handle the environment. Students should play through the tutorial and let you know if they have any questions about how the reproduction interface works, or other aspects of the game.

Discussion of Play (~15 minutes)

[The goal is to get students to reflect on how the game and their choices relate to course content and be aware of the relationship in the future]

Tell the students to pause the game, and that they will get to play more next period. Lead a discussion of the actions the student took in the game, the obstacles they encountered, and how they relate to the real world context of *Tetrahymena*, then hand out the student worksheet and have them fill it out as they continue playing.

After students have played the game, discuss the experience with the students and go through the conclusion questions.

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Goals/Overview for the Discussion:

Reflect on play experience and tie it to natural selection, reproducing sexually/asexually, reproductive fitness, how an organism interacts with other organisms and its environment.

Talk about general experience of playing the game and what it's like for *Tetrahymena* in the environment. Speak about reproductive choices and how it affects the *Tetrahymena*'s fitness in the environment and how it changes over time.

(~5-10 minutes)

Ask the class to stop and hand out the question sheets. Tell them to fill out the sheet and discuss answers with neighbors. Leave ~10-15 minutes at the end of class for discussion. Don't rush through questions. Don't feel pressured to finish all the questions by the end of the class period. Students can finish discussion questions for homework. We can discuss them tomorrow.

An example discussion:

Possible Topics for Discussion

Life of a *Tetrahymena*

Start off by discussing what the students found exciting about the game. Try to get students to talk about their experience with the game- what the environment and game were like. Draw on what was most interesting to them in the subsequent topics.

Conclusion Question

What was the most memorable thing that happened while you were playing?

Homework Questions

Draw a food web for the organisms in the game.

Possible Further discussion

What was life like as a *Tetrahymena*? What challenges does it face? Did they have trouble finding food, or run into other *Tetrahymena* eating food?

How threatening were the predators? Did this change as their traits shifted?

Variation and Traits

Start by talking about what choices students made in terms of the traits of their cells and tying this back to natural selection.

Conclusion Questions

What traits were most helpful in "Stillwater Pond"?

How did those traits help the cell survive?

Did you choose cells with the same traits the whole time you played or did you try different sets of traits? What made you change or what made you stay with one set?

Did any other student choose a set of traits that worked well? Which traits?

Homework Questions

Give another set of traits or behaviors another student used to try

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and help their cell survive. How was this different from what your cell did?

How did the set of traits from question 2 affect the survival or feeding efficiency of your cell compared to theirs?

How do the organisms in the food web exert selective pressures on each other? Give two specific examples of how one organism can exert pressure on another

NOTE: Make sure students talk about what traits they selected for. Compare with other students so they have enough information to complete the homework questions.

Misconceptions to Address

Due to the nature of the game, it is easy to get a sense that there is an intelligent choice being made by *Tetrahymena*. If this becomes an issue, directly address the contrasts between the game and the world, and have the students reflect on them. In the game, you control a cell, but in the world *Tetrahymena* act reflexively to their conditions. In the game you look at one cell each generation and the black and white distinction of whether it lives and reproduces or dies. In the real world, it'd be about a population and whether, over many generations with a trait, the average survival rate was higher.

Possible Further discussion

Ask one of the students what their cell history looks like. It may be helpful to draw axis on the board, and ask where they went from the center (where the initial cells start).

Ask students what choices they made and what their reproduction histories look like. Why did they make those choices? Why did they choose to focus on cells with high [trait] ? What did they expect to happen and did it work that way? If they started going one way then changed why did they change?

Ask for a show of hands of how many other students ended up in that section of the graph as well. If the student changed direction ask if other students did as well.

Ask which students went in other directions. Pick one or a few and ask them why they did that.

When students selected different traits each generation, how did this affect how they found food or avoided predators?

If most of the students went with the same traits, or students with some traits seemed to do better than others bring up how environments favor some traits. If cells with these traits do obtain more food, survive longer, and reproduce, then there are more of them than the less favored cells.

If the students split among the traits and didn't notice much difference in survival between strategies, you can talk about how an environment that doesn't favor some traits can lead to variation in a population. If there isn't a pressure to have some traits to survive, cells with lots of traits flourish, which actually helps the population if a new pressure is applied, if conditions change. An example

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might be if a new species is introduced or the climate changes.

Ask how many generations students had. And how many cells were in their current population?

Reproduction

One of the key parts of natural selection is reproductive fitness; tie this into what reproductive choices students made and how this impacted their survival and experience.

Conclusion Question

Did you try reproducing sexually and asexually? How did they differ in the game?

Homework Questions

When was it good to reproduce sexually? What about asexually?

Misconception

If students aren't dying, they may have the misconception that sexual reproduction is always better. Be prepared to briefly discuss some of the benefits and costs of sexual reproduction.

Students are not following the same cell whose traits are changing, but the offspring of the cell. The game portrays the population evolving over time, and you are observing a representative of the population to observe evolution and natural selection.

In the game, students have their choice of mates, but in the real world other factors influence mate availability and selection, such as the proximity of potential mates. Those that are more reproductively fit would be a larger portion of the population, including those within the area.

Possible Further discussion

If students chose not to reproduce sexually or asexually, why did they make that choice?

Pair Share: If you have trouble getting students to talk, have them pair off with the student next to them and briefly find something that was different about how they played. Don't let them talk for more than two minutes, to keep the class moving. Have some groups share what differences they found, and use that to prompt more discussion.

This discussion is also a good opportunity to answer any questions about how the game works, what symbols mean, how to do something, etc. It is particularly important that students have a good understanding of the graph, so they can build on this in the next lesson.

Class Period 2

NOTE: The second level has few hazards, many obstacles, some predators and less food than before. Expect students to favor high maneuverability and high feeding efficiency to best be use the available food, evade predators among the obstacles, and explore the level.

**Intro and worksheet
(~5 minutes)**

At the beginning of class, hand out a log that has the conclusion questions. At the end of class, hand out another HW sheet.

Today, make sure the students have the worksheet to fill out as they play. Remind students to fill out the sheets as they progress through the game, especially when they reproduce.

**Reflective Play Session
(~15 minutes)**

[The goal is to have students play the game being more attentive to their choices, behavior patterns, and the environment in the game]

After handing out the worksheets, let the students play more, but walk around making sure they are filling in the sheets as they go, especially when reproducing.

Feel free to let students discuss actions and compare experiences while playing, or focus on their own game. However, be careful about competition, repeated failure, and/or discouraged students. **The goal of the game is not to have the largest population size. Be clear that the game is about exploring *Tetrahymena* in their world and learning what makes them more or less likely to survive.**

**Discussion and
conclusions (~20
minutes)**

Lead the students in another discussion, but this time use the conclusion questions as a guide. Draw on the previous discussion, comparisons between experiences, and the information the students' filled in on their worksheets.

Topics for discussion

Variability and Traits

Start by talking about what choices students made in terms of the traits of their cells and tying this back to natural selection.

Conclusion Question

What traits were helpful in Small puddle?

How did these traits help the cell survive?

Homework Questions

What information did you learn from talking to other students about the game that was useful when you played it the second time?

Misconceptions to Address

Due to the nature of the game, it is easy to get a sense that there is an intelligent choice being made. See Day 1 for more on how to address this.

Possible Further discussion

Cell-vival Game: TEACHER PROTOCOL

A lot of this discussion will reference the previous discussion. Use this to transition into comparing the traits favored in the different environments.

Fitness in Context

Have students compare their experiences and choices of traits between the two environments.

Conclusion Question

Were these traits different from the ones that were helpful in Stillwater pond?

What factors affect the survival rate of an organism?

Homework Questions

Why did these environments favor different traits? Compare and contrast the levels.

Did your reproductive choices for the cell change over generations?

How? Why?

Did the way you responded to challenges outside of reproduction change over generations? How? Why?

Misconceptions to Address

Unlike the other misconceptions, this is not necessarily fostered by the game but it may be good to point out that evolution is not moving in the direction of an ideal, but fitness is determined by the changing environment.

Possible Further discussion

How could fitness change within the same environment over time?

How could the evolution of one organism change the evolution of other organisms within the environment? (Co-evolution)

Wrap Up

Try to get the students to integrate their experiences with the game and the concepts discussed in a way to tie to other material covered before or plan to cover later.

Homework Questions

How did this help you better understand the microscopic environment that *Tetrahymena* live in?


What factors affect the survival rate of an organism in the real world, that are not represented in the game?

Possible Further discussion

Tying it back into larger questions and contexts such as how selective pressures affect all organisms in all sorts of environments.

APPENDIX D

Game Module Student handout

	ASSET Student Activity
	How does natural selection work? What do <i>Tetrahymena</i> do?

Objective

To learn more about the world of *Tetrahymena* and how that world can influence the characteristics of a population over multiple generations.

Background

In this activity, you will play the role of a *Tetrahymena* in a game called Cell-vival. You'll explore its ecosystem, see what food, predators, and obstacles looks like at the microscopic scale. You'll even get to choose when to reproduce and pick which offspring to control next.

In the real world, *Tetrahymena thermophila* is a small single-celled ciliate that typically lives in freshwater systems and eats bacteria and small organic particles. It is preyed on by a number of larger protozoans, rotifers, and copepods, some up to 100 times larger than a *Tetrahymena*.

Here is some terminology that may come up in your discussion and homework:

Trait

A trait is an observable characteristic of an organism, like hair color, or mouth size. In this game, you are only interested in heritable traits, those that can be passed on from one generation to the next.

Genetic variation

Genetic variation refers to the differences in the heritable traits of a group of organisms. Even in a group of organisms that all look very much alike, like the dandelions in your lawn, there are small differences (variations) in genetic information. Aside from identical twins, no group of organisms is ever completely identical. These variations may make an organism more (or less) likely to survive and produce healthy offspring when the environment changes.

Environment

The environment consists of external surroundings including all of the living (e.g. animals and plants) and nonliving (e.g. terrain and energy) factors that surround and affect the survival and development of an organism or population.

Evolution

Evolution is the change in traits of a population of organisms over time.

Evolution can happen through 3 processes:

1. **Mutation:** General term for changes in an organism's hereditary information. Mutations can occur for a number of reasons, and create new genetic variations.
2. **Genetic drift:** Random change in the genetic variation of a population from generation to generation. It often occurs in traits that are not under selective pressure.
3. **Natural selection:** The non-random and gradual process of natural variation by which observable traits, including physiology and behaviors, become more or less common in a population.

Natural selection

In natural selection, variations that increase an organism's chances of survival and reproduction and are heritable (can be passed on to offspring) become more common in a population from generation to generation. Natural selection often drives evolution. Natural selection favors traits that improve fertility, speed up development, and make mating more successful – anything that improves the chances of producing healthy offspring.

In order for natural selection to occur, a population must have:

1. **Variation.** Organisms show individual variation in appearance and/or behavior. These variations may involve body size, hair color, facial markings, mating behavior, feeding behavior, or number of offspring. Some variation may not be observable, but may become important if environmental conditions change.
2. **Inheritance.** Some traits are consistently passed on from parent to offspring. These traits, such as number of fingers or blood type are heritable. Other traits are strongly influenced by environmental conditions and are non-heritable, like the ability to speak Spanish or ride a bike.
3. **High rate of population growth.** Most populations have more offspring each year than local resources can support leading to a struggle for resources. Because there are limited resources, many individuals die.
4. **Differential survival and reproduction.** Individuals possessing traits that make them better at competing for limited local resources (such as food, shelter, or mates) will contribute more offspring to the next generation.

Fitness

Fitness is the ability of an organism to both survive and reproduce. The higher the fitness of an organism, the more likely it will have many surviving offspring.

Predator

A predator is an organism that feeds on another organism.

Prey

A prey is an organism eaten by other organisms.

Selective pressure

Selective pressure occurs when something in the environment makes one organism more able to reproduce than another.

For example, when you take an antibiotic to treat an infection, bacteria that aren't resistant to the antibiotic die and have no more offspring. If there were genetic variants in the original population that are resistant to the antibiotic, they will begin to reproduce and take advantage of the resources that they previously had to share. They will produce many offspring and after a few generations, nearly all the bacteria in the population will be resistant. In this case, the antibiotic exerts a selective pressure on the original bacterial population. Because the selective pressure was very strong, the inherited trait (antibiotic resistance) quickly spread throughout the population.

Adaptation

Adaptation is the evolutionary process in which a species becomes better able to live in its habitat.

For example, birds that eat insects have long thin beaks, while those that eat seeds have short powerful, seed-crushing beaks.

Co-evolution

Co-evolution occurs when a change in the genetic composition of one species (or group) prompts a genetic change in another. Often this change prompts another change in the first species, forming cycle. For example, flowers and pollinators like bees and hummingbirds have co-evolved.

Coevolution is likely to happen when different species have close ecological interactions with one another. Examples of such ecological relationships include:

1. **Predator/prey and parasite/host relationships:** One species uses and harms the other to improve its own survival. For example, a hawk eating mice.
2. **Competitive species:** Two species that compete for the same resources. For example, lions and cheetahs both hunt other mammals in the same area.
3. **Mutualistic species:** Two species that both benefit from a relationship. One example is flowers and bees: flowers produce nectar that feeds bees, while bees transfer pollen so the flowers can reproduce. Another would be cows and their gut bacterial: the cow provides a safe environment (its stomach) and food for the bacteria, and the bacteria break down the cellulose in the grass into things the cow can digest.

Sexual Reproduction

Sexual reproduction is a process that creates a new organism by combining half the genetic material of two parent organisms. Genetic variation is caused by independent assortment of genes and crossing over during meiosis. Mutation may also occur during this process if the mutation occurs in the parent cells that produce the gametes.

Asexual Reproduction

Asexual reproduction, or cloning, is a process by which offspring arise from a single parent, and inherit the identical genes of the parent. This means that the only source of variation from the parent's traits is random mutation.

Mitosis

A form of cell division in which one cell creates two genetically identical "daughter" cells. For single-celled organisms, a form of asexual reproduction.

Meiosis

A more complicated form of cell division, in which one cell becomes four gamete cells, each with half the genetic information of the original cell. These gametes are then used for sexual reproduction in multi-cellular organisms, with gametes from two parents forming a complete set of information for the offspring. In single-celled organisms, other, more complex processes are used to allow for sexual reproduction.

Here is a step-by-step example of natural selection in action:

- Let's say there is a population of *Tetrahymena* that vary in swimming speed. Some swim faster, some swim slower.
- If they are in an environment with lots of predators that they need to outrun, then the faster the *Tetrahymena*, the more likely it is to survive and to reproduce. Faster swimming allows the *Tetrahymena* to produce more offspring, so it increases its reproductive fitness.
- If swim speed is heritable (can be passed on to offspring), that means in the next generation there will be more *Tetrahymena* that swim fast. Since more of the fast swimmers reproduced than slow swimmers, and they pass on their fast swimming, there are more fast swimmers in the new generation than slow swimmers.
- If the environment continues to favor *Tetrahymena* that swim faster, then each generation will see more of the population swimming faster and a smaller part of the population swimming slowly. Over multiple generations, these shifts can add up so the population is very different than it used to be; in this case, we'd see a population of *Tetrahymena* that swam much faster, on average, than the original population.

In this example, the predators that eat slow swimmers are an example of a selective pressure, a factor that makes some trait (the ability to swim fast) important for reproductive fitness.

Your teacher will help you find and open the game. For today, you will play an introductory level. The object is to stay alive.

Day 1

Discussion and after class questions:

1. What was the most memorable thing that happened while you were playing?

2. What traits were most helpful in the “Small Puddle”? How did those traits help the cell survive?

3. Did you choose cells with the same traits the whole time you played, or did you try different sets of traits? What made you change or what made you stay with one set?

4. Did any other student choose a set of traits that worked well? Which traits?

5. Did you try reproducing sexually and asexually? How did they differ in the game?

Day 1 Homework Questions

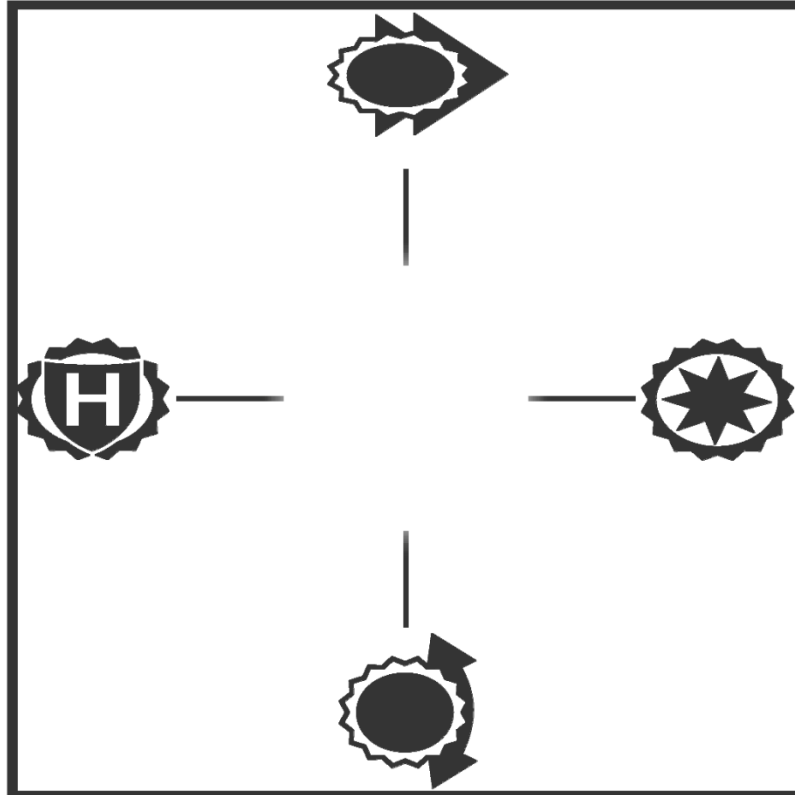
1. Draw a food web for the organisms in the game.
2. How do the organisms in the food web exert selective pressures on each other? Give two specific examples of how one organism can exert pressure on another.
3. What choices did you make in the game that made it harder for your cell to survive?

Day 2

As you play the game today, keep a record of your choices and answer these questions.

Reproduction

Each time you reproduce, record the point for the new generation on the graph below and number it.



Day 2 Discussion questions:

1. What traits were helpful in the Stillwater Pond? How did these traits help the cell survive?
2. Were these traits different from the ones that were helpful in the Small Puddle?
3. If you played a level with lots of hazards and not much food, what traits would you expect to help a *Tetrahymena* survive? Why?
4. What factors affect the survival rate of an organism?

Day 2 Homework Questions

1. What information did you learn from talking to other students about the game that was useful when you played it the second time?
2. Why did these environments favor different traits? Compare and contrast the levels.
3. Did your reproductive choices for the cell change over generations? How? Why?
4. Did the way you responded to challenges (other than through reproductive choices) change over generations? How? Why?
5. How did this better help you understand the microscopic environment that *Tetrahymena* live in?
6. What factors affect the survival rate of an organism in the real world, that are not represented in the game?

APPENDIX E

Online Assessment Form

10/31/2014

Qualtrics Survey Software

1

First name and last initial.
(For example: Drew Smith would be "Drew S.")

What class are you in? Please include your instructor's name.
(For example "Mr. Smith's earth science class")

What grade?

9th

☐

10th

☐

11th

☐

12th

☐

2

Compared to sexual reproduction, asexual reproduction tends to create ____ offspring and ____ variation in those offspring given the same amount of time and energy.

- ☐ less; more
- ☐ less; less
- ☐ more; less
- ☐ more; more

Natural selection occurs in:

- ☐ populations.
- ☐ niches.
- ☐ individuals.
- ☐ communities.

Which of the following conditions are necessary for natural selection? Select all that apply.

- ☐ Mates are selected based on a mating display that indicates fitness.
- ☐ Some traits are heritable and passed on to offspring.
- ☐ The population is capable of sexual reproduction.
- ☐ There are at least two species competing for limited resources.
- ☐ There is variation in traits within the population.
- ☐ More offspring are produced than survive to reproduce.

Which of the following is the best example of natural selection?

<https://cornell.qualtrics.com/ControlPanel/Ajax.php?action=GetSurveyPrintPreview&T=YCTNw>

1/4

- ☐ Repeated friction or damage to an area of skin over time causes a resistant callus to form.
- ☐ A population of fish changes over time due to immigration of new fish from other regions.
- ☐ An indoor housecat lives about 10 years longer than an outdoor housecat.
- ☐ The average shell thickness of a turtle population increases over time in response to high predation.

Which of the following is the best example of a selective pressure?

- ☐ In a cave environment where there is no light and plenty of food, the skin color of a population of lizards gradually becomes more diverse.
- ☐ A new disease begins killing only the birds that nest in a certain species of tree and are too old to lay eggs.
- ☐ An invasive species of octopus arrives in a bay and begins eating the largest of the local clams.
- ☐ A group of hunters visits a remote island, kills a number of local wild boars, then leaves and never returns.

3

Briefly describe what makes one organism "more fit" than another, in the context of natural selection.

A population of cougars (a type of large cat) have recently moved into the habitat of a population of mountain goats and have begun preying on the goats. Give an example of how this change may impact the population of mountain goats.

Beyond there being less goats, how might the population change?

For organisms that sexually reproduce, how do they select a mate?

4

In the deep sea, there are ecosystems that don't get their energy from the sun, but from geothermal vents. Instead of photosynthetic plants, microbes that live off the chemicals from the vents form the base of the food chain. These microbes are eaten by clams and scallops, which are then eaten by larger predators like crabs and shrimp.

Name at least one change to the environment that would create selective pressures on a population of these clams, and explain how it creates this pressure.

What changes would you expect to see in the population of clams in response to that pressure?

5

Please rate your interest in the following activities:

	No interest	.	.	Some interest	.	.	High interest
Learning about science	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Doing interactive science activities	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Reading about science	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Discussing science in class	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Discussing science outside of class	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Discussing biology in class	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Discussing biology outside of class	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>

Please rate your interest in the following topics:

	No interest	.	.	Some interest	.	.	High interest
Science	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Biology	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Natural selection	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>

6

How effective or ineffective were the content and activities you did in class to learn about natural selection?
Can you give examples of specific things that were enjoyable and helpful or that could be improved?

Do you have any suggestions about how to teach this topic in the future?

Did you play the game Cellvival in class?

Yes



No



7

How does Cellvival differ from how things work in the real world?

Specifically, how are reproductive choices made in the real world compared to how they are made in the game?

APPENDIX F

Qualitative Coding Reference

- Q6 “Briefly describe what makes one organism "more fit" than another, in the context of natural selection.”

Dimensions:

- C1 length: number of words (scale)
- C2 depth: (scale 1-7)
- C3 mentions environment or competitors (y/n)
- C4 mentions survival (y/n)
- C5 mentions reproduction (y/n)
- C6 mentions “pass on traits” (y/n)
- C7 mentions reproducing more than others (y/n)
- C8 used game-based example (y/n)
- C9 used other specific example (y/n)

Depth rubric:

- 1 Idk or joke
- 2 Unexplained or tautology: Its better, traits more advantageous, etc.
Or specific traits: stronger, faster, etc.
- Generally on par with, adjusted up or down for quality:
- 3 it can survive better (or better than others)
- 4 it can survive to reproduce
- 5 it can survive to pass on its traits
- 6 it has more offspring to pass on its traits better, and become more of the population
- 7 6+

- Q7 “A population of cougars (a type of large cat) have recently moved into the habitat of a population of mountain goats and have begun preying on the goats. Give an example of how this change may impact the population of mountain goats.
Beyond there being less goats, how might the population change?”

Dimensions:

- | | |
|-----|---|
| C1 | length: number of words (scale) |
| C2 | depth: (scale 1-7) |
| C3 | mention: specific adaptation (at least 1) |
| C4 | mention; whatever genes/traits help survive |
| C5 | mention; some goats survive to pass on traits |
| C6 | mention; offspring more resistant to predation |
| C7 | mention: change in one population affect another population
(ie changes to grass, cougars, etc.) |
| C8 | mention; more than 2 generations
(ie not just now+offspring, but further, or speciation) |
| C9 | mention; variation or diversity changes |
| C10 | mention; specifically weak dying and others living |

Depth rubric:

- | | |
|----|--|
| +1 | for accurately discussing effects on other populations (cougars, grass, etc.)
as well as goats |
| 1 | Idk or joke |
| 2 | General and superficial:
“they adapt to it” or “less goats”, “more cougars”, “more grass”,
etc. |
| 3 | Specify appropriate adaptation:
Faster, move habitat, hide, defenses, etc. |
| 4 | Goats that survive will reproduce/pass on genes |
| 5 | Whatever traits help goats survive get passed on, so next
gen/population become more resistant to predation |
| 6 | 5+ |
| 7 | 6+ (so 5 + other pops + being well done) |

Q8 “For organisms that sexually reproduce, how do they select a mate?”

Dimensions

- C1 length: number of words (scale)
- C2 depth: (scale 1-7)
- C3 mention; assess a marker (mating display, trait, etc.)
- C4 mention; perceived as more fit
- C5 mention; quality of offspring (better, more fit, stronger, survive, etc.)
- C6 mention: viability (same species, viable offspring, can reproduce etc.)
- C7 mention; competition with other mates
- C8 mention: location based restriction (ie mates they can find/are in the area)
- C9 use example from game

Depth rubric:

- 1 Idk or joke
- 2 give a trait/most attractive OR just same species and able to mate
- 3 trait that that species values, multiple examples OR is ‘most fit’
- 4 trait that indicates something about fitness
- 5 will make the best offspring
- 6 will make best offspring who will then produce more offspring, etc.
- 7 6+